US009339343B2

(12) **United States Patent**
Swarup et al.

(10) **Patent No.: US 9,339,343 B2**
(45) **Date of Patent: May 17, 2016**

(54) **USER INTERFACE METHODS FOR ALTERNATE TOOL MODES FOR ROBOTIC SURGICAL TOOLS**

(75) Inventors: **Nitish Swarup**, Sunnyvale, CA (US); **Scott E. Manzo**, Shelton, CT (US)

(73) Assignee: **INTUITIVE SURGICAL OPERATIONS, INC.**, Sunnyvale, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **13/533,277**

(22) Filed: **Jun. 26, 2012**

(65) **Prior Publication Data**

US 2013/0006268 A1 Jan. 3, 2013

Related U.S. Application Data

(63) Continuation of application No. 12/028,755, filed on Feb. 8, 2008, now Pat. No. 8,224,484.

(60) Provisional application No. 60/976,460, filed on Sep. 30, 2007.

(51) **Int. Cl.**

A61B 19/00	(2006.01)
A61B 18/14	(2006.01)
A61B 17/00	(2006.01)

(52) **U.S. Cl.**

CPC ***A61B 19/2203*** (2013.01); *A61B 18/1445* (2013.01); *A61B 19/5212* (2013.01); *A61B 19/56* (2013.01); *A61B 2017/00477* (2013.01); *A61B 2019/2223* (2013.01); *A61B 2019/2234* (2013.01); *A61B 2019/2242* (2013.01); *A61B 2019/2246* (2013.01)

(58) **Field of Classification Search**

CPC A61B 19/2203; A61B 2017/00477; A61B 2019/2246; A61B 19/5212; A61B 19/56; A61B 2019/2223; A61B 18/1445; A61B 2019/2242

USPC 700/245; 606/1, 130

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,464,652 A 8/1984 Lapson et al.
4,772,882 A 9/1988 Mical

(Continued)

OTHER PUBLICATIONS

U.S. Appl. No. 12/028,750, filed Feb. 8, 2008.

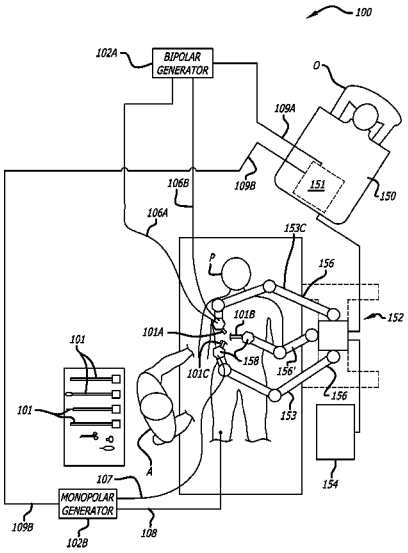
(Continued)

Primary Examiner — John Q Nguyen
Assistant Examiner — Rodney P King

(57) **ABSTRACT**

In one implementation, a method is disclosed in which a lock sensing mode is entered for a robotic surgical instrument. In the lock sensing mode, the degrees of freedom of movement in the robotic surgical instrument are switchably reduced. Further in the lock sensing mode, one or more end effectors of the robotic surgical instrument are switchably clamped together in the robotic surgical instrument. An increased level of torque may also be applied to the end effectors to increase a gripping force applied by the one or more end effectors in response to the reduced degrees of freedom of movement in the robotic surgical instrument.

20 Claims, 32 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

5,327,529	A	7/1994	Fults et al.	
5,562,655	A	10/1996	Mittelstadt et al.	
5,611,040	A	3/1997	Brewer et al.	
5,914,718	A	6/1999	Chiu et al.	
5,923,139	A	7/1999	Colgate et al.	
6,152,673	A	11/2000	Anderson et al.	
6,184,868	B1	2/2001	Shahoian et al.	
6,459,926	B1	10/2002	Nowlin et al.	
6,493,608	B1	12/2002	Niemeyer	
6,714,839	B2	3/2004	Salisbury, Jr. et al.	
6,799,065	B1	9/2004	Niemeyer	
8,224,484	B2	7/2012	Swarup et al.	
2002/0032451	A1	3/2002	Tierney et al.	
2002/0032452	A1	3/2002	Tierney et al.	
2002/0120188	A1*	8/2002	Brock et al.	600/407
2003/0195664	A1*	10/2003	Nowlin et al.	700/260
2004/0015079	A1	1/2004	Berger et al.	
2005/0043719	A1*	2/2005	Sanchez et al.	606/1
2005/0215866	A1	9/2005	Kim	
2005/0222587	A1	10/2005	Jinno et al.	
2006/0060630	A1	3/2006	Shelton, IV et al.	
2008/0033240	A1	2/2008	Hoffman et al.	
2008/0046122	A1	2/2008	Manzo et al.	
2009/0088774	A1	4/2009	Swarup et al.	
2009/0088775	A1	4/2009	Swarup et al.	
2012/0179169	A1	7/2012	Swarup et al.	

OTHER PUBLICATIONS

Rockall, Timothy A., "The da Vinci Telerobotic Surgical System," Chapter 8 in Primer of Robotic & Telerobotic Surgery, Eds. Garth H. Ballantyne et al., Pub. by Lippincott Williams & Wilkins, Philadelphia, 2004, pp. 57-60.

Taylor, Russell H. et al., "A Telerobotic Assistant for Laparoscopic Surgery," IEEE Engineering in Medicine and Biology, May/Jun. 1995, pp. 279-288, vol. 14, Issue 3, IEEE.

U.S. Appl. No. 12/028,750 Final Office Action mailed Sep. 27, 2011, 10 pages.

U.S. Appl. No. 12/028,750 Office Action, mailed Apr. 1, 2011, 11 pages.

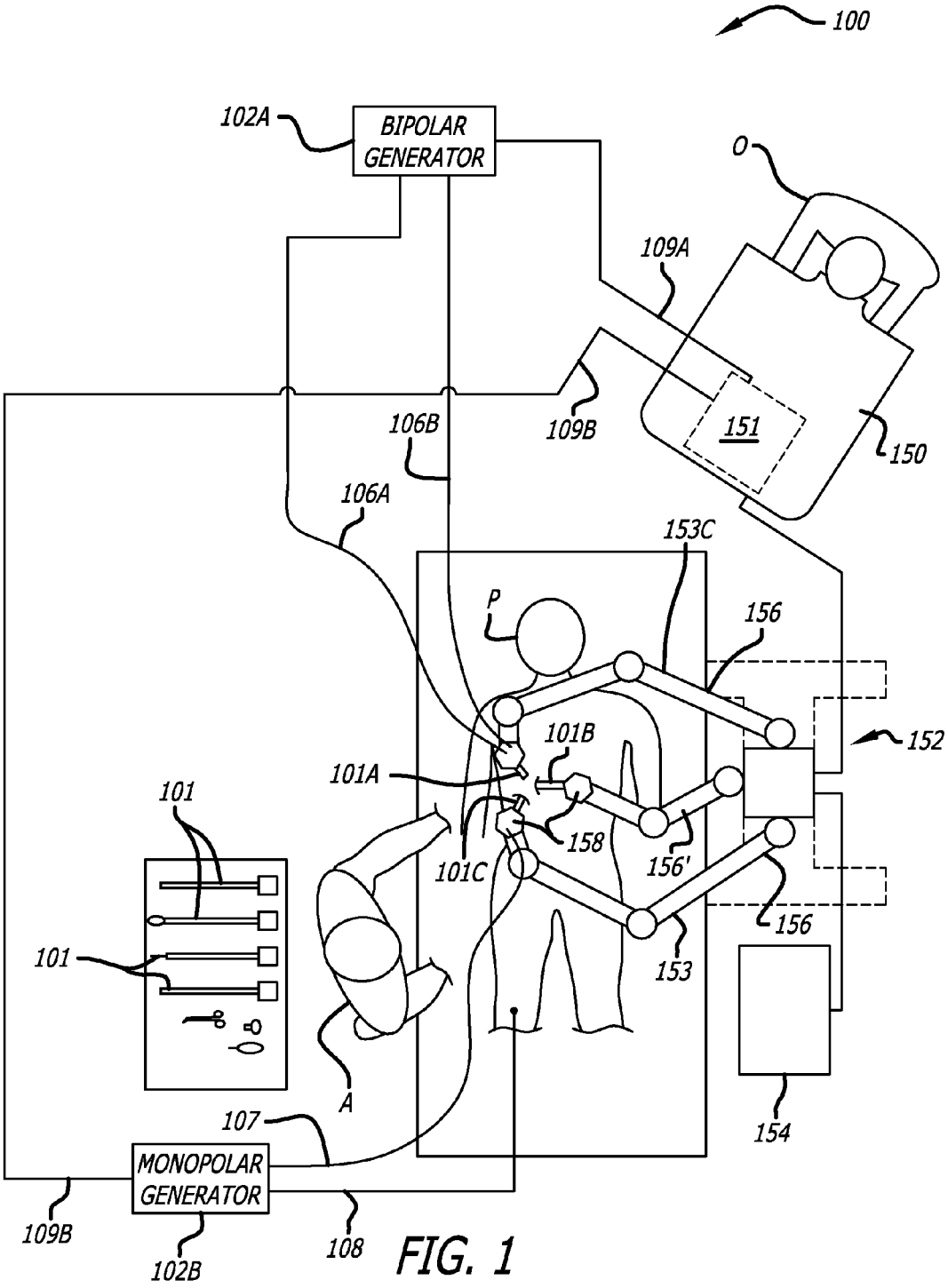
Vertut, Jean and Phillipe Coiffet, Robot Technology: Teleoperation and Robotics Evolution and Development, English translation, Prentice-Hall, Inc., Inglewood Cliffs, NJ, USA 1986, vol. 3A, 332 pages.

U.S. Appl. No. 12/028,755 Final Office Action mailed Sep. 27, 2011, 12 pages.

U.S. Appl. No. 12/028,755 Office Action, mailed Mar. 29, 2011, 12 pages.

U.S. Appl. No. 13/429,745 Office Action mailed Jul. 11, 2012, 8 pages.

* cited by examiner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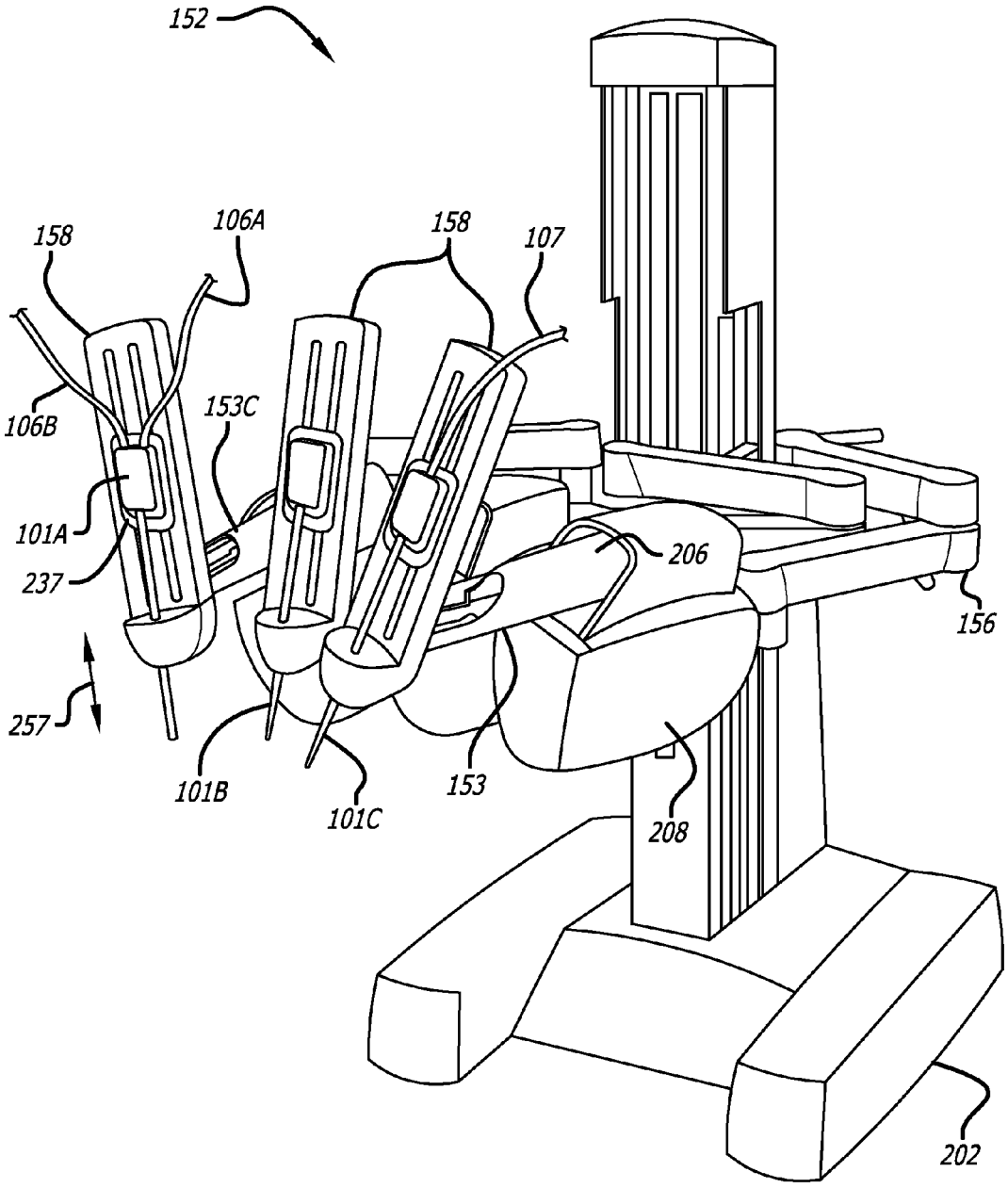
102A
BIPOLAR GENERATOR
O
109A
109B
106B
151
150
106A
153C
P
156
152
101B
101A
101
158
156'
101C
156
101
153
A
154
107
MONOPOLAR GENERATOR
109B
102B
108

FIG. 1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158
106A
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107
106B
153C
101A
237
206
156
257
101B
101C
153
208
202

FIG. 2A

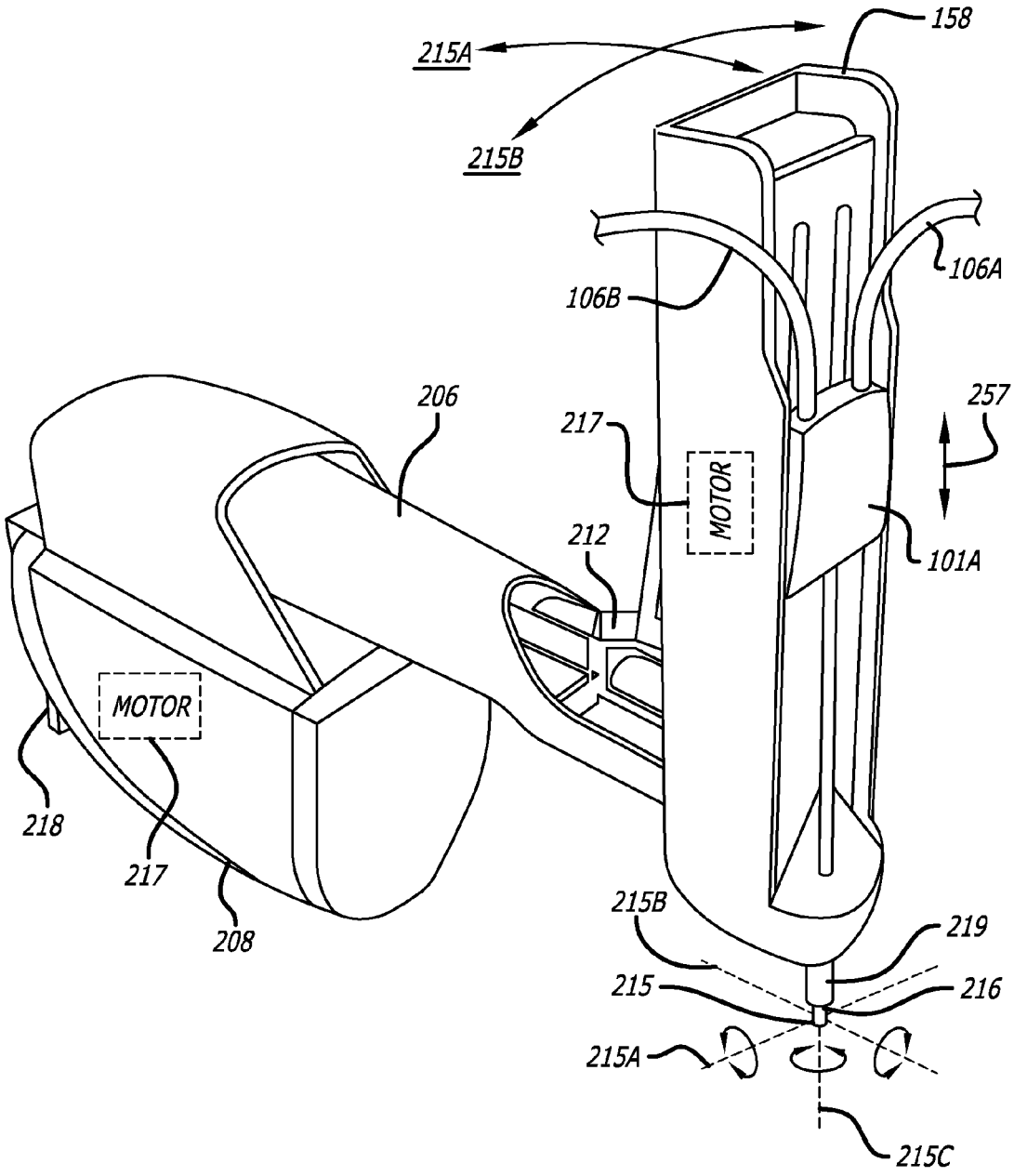

158
215A
215B
106A
106B
206
217
257
MOTOR
212
101A
MOTOR
218
217
208
215B
219
215
216
215A
215C

FIG. 2B

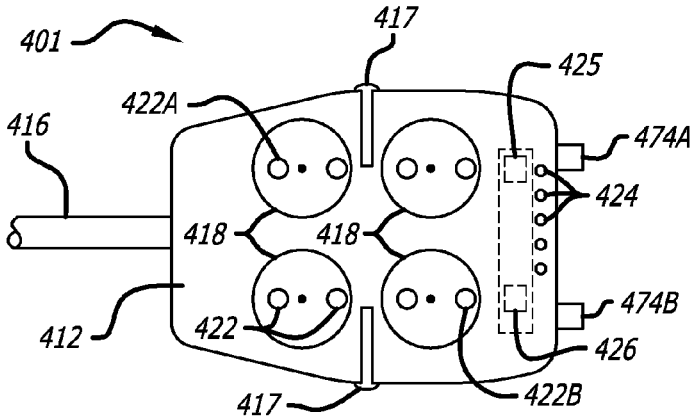


FIG. 4F

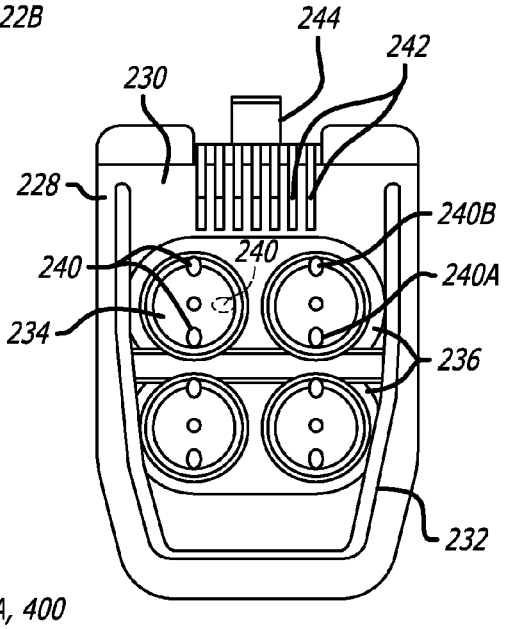


FIG. 2D

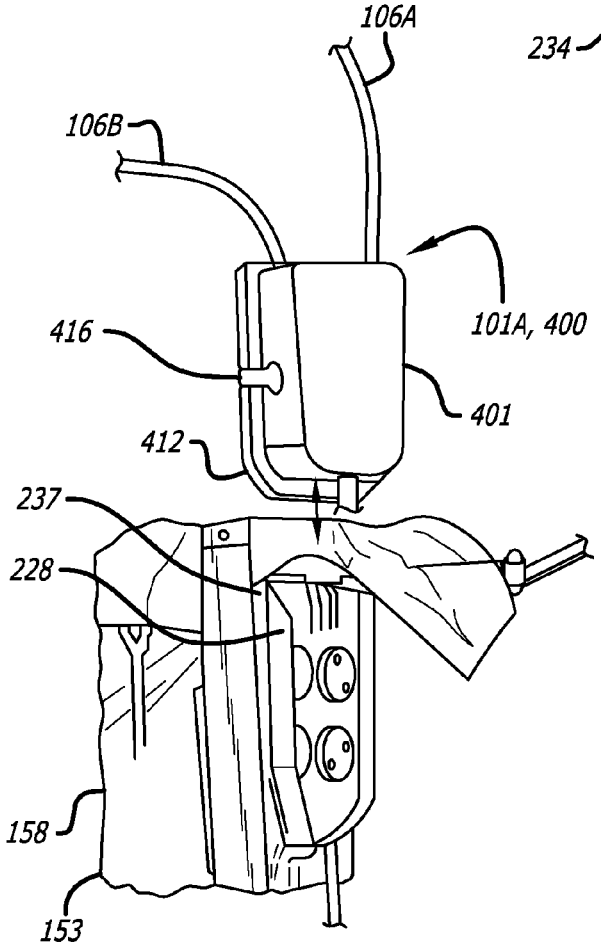


FIG. 2C

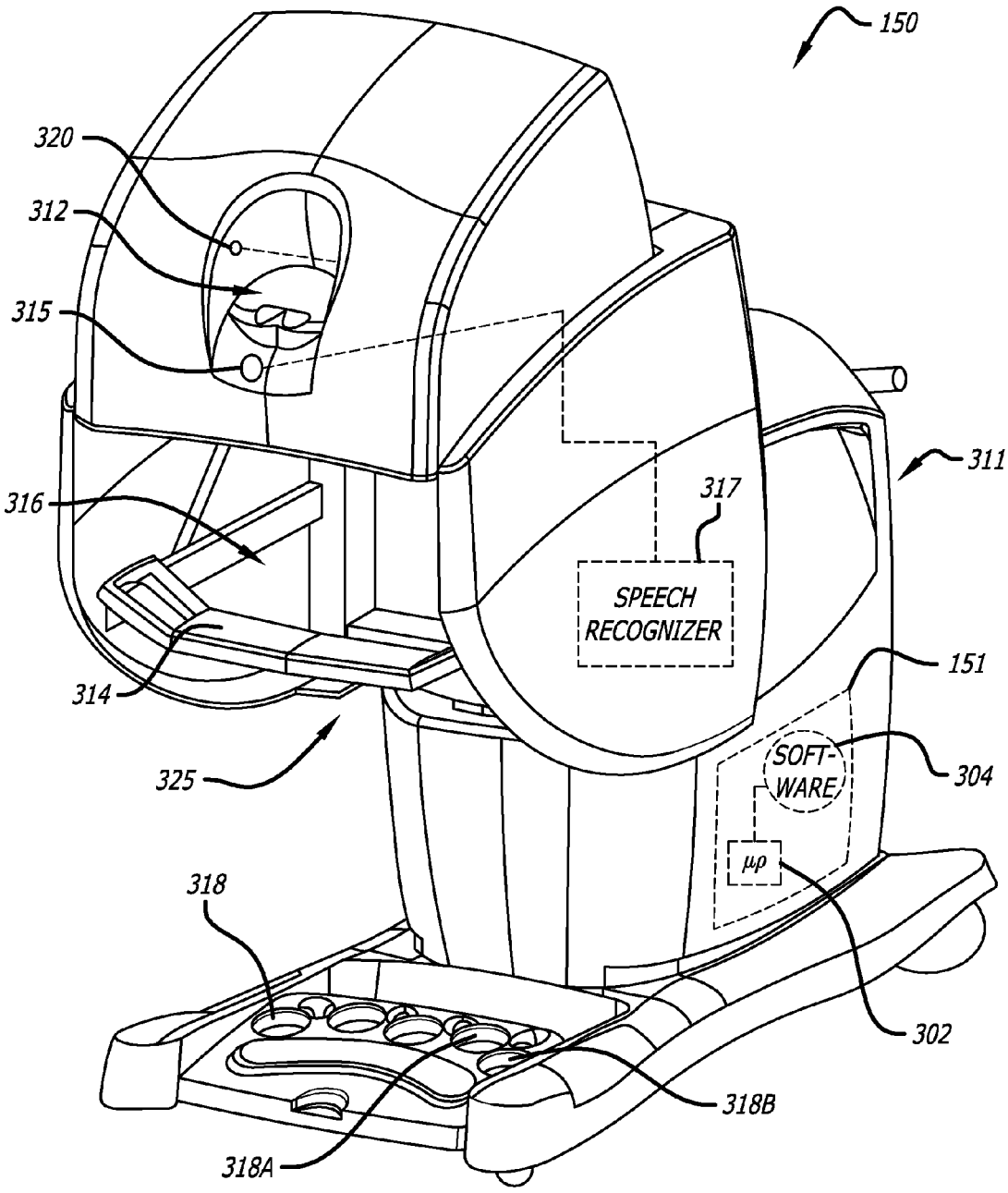
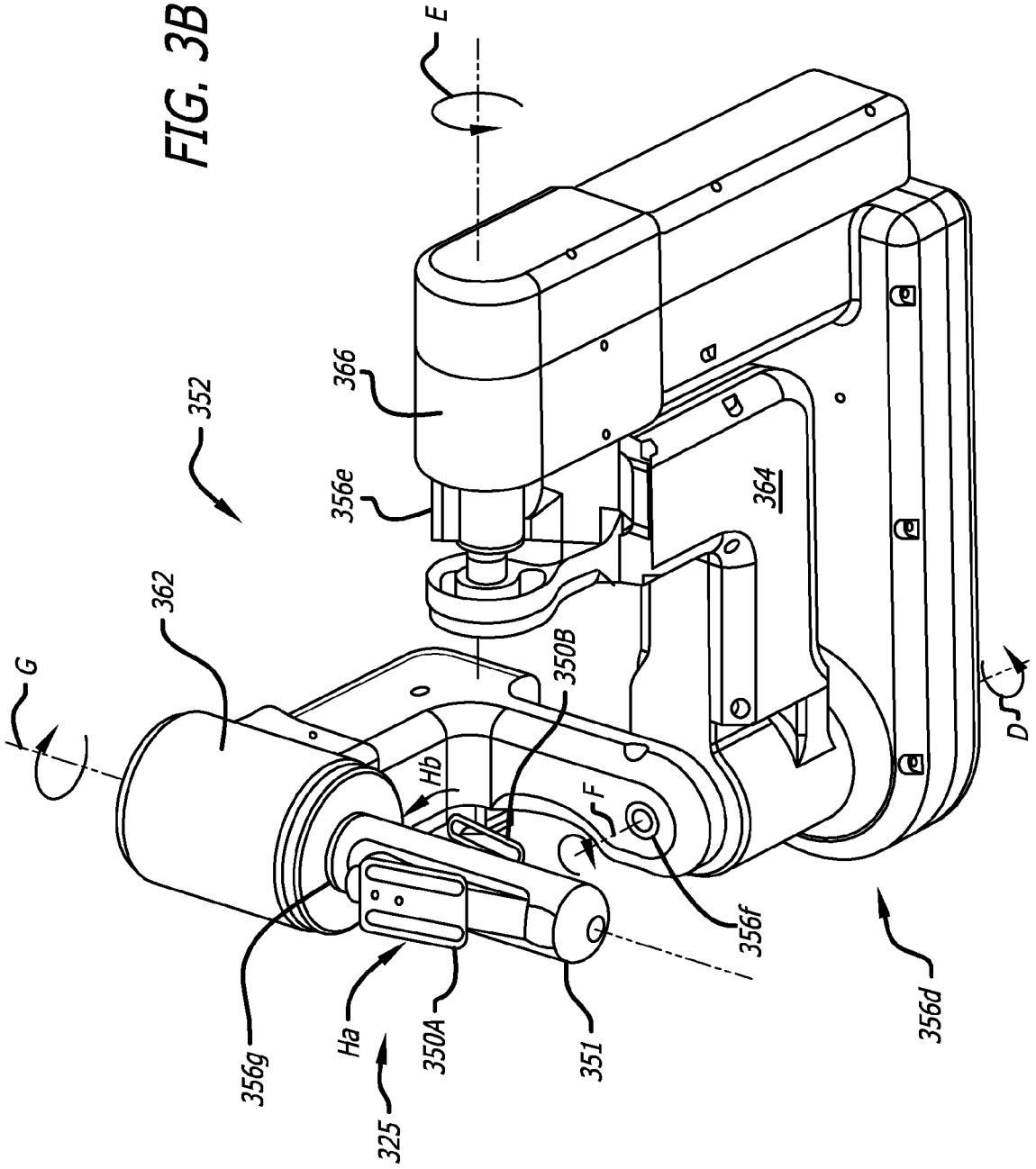

150
320
312
315
316
314
325
311
317
SPEECH RECOGNIZER
151
SOFT-WARE
304
μp
318
302
318B
318A

FIG. 3A

FIG. 3B


E
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362
350B
G
Hb
F
D
356f
356g
Ha
350A
351
356d
325

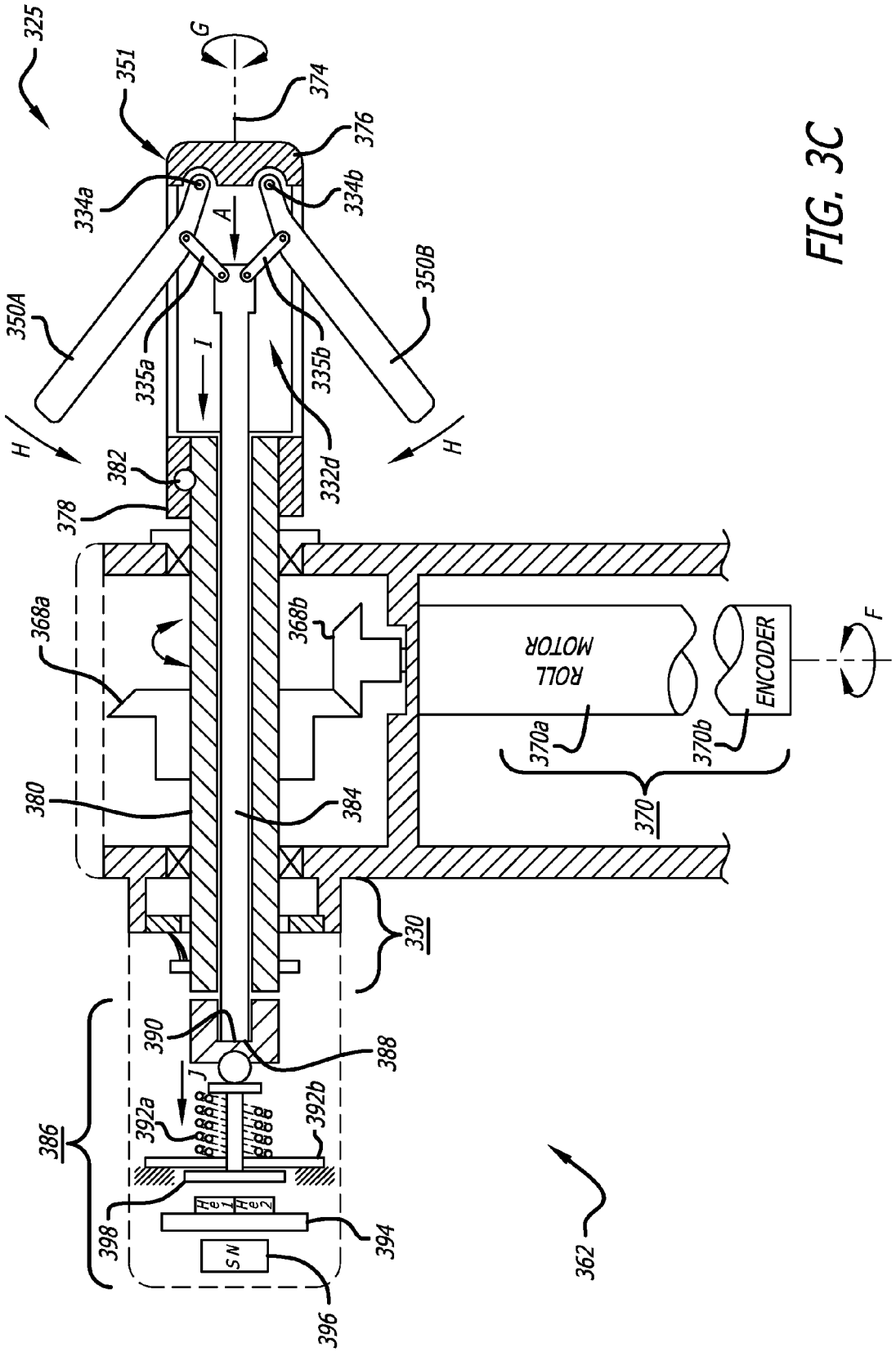
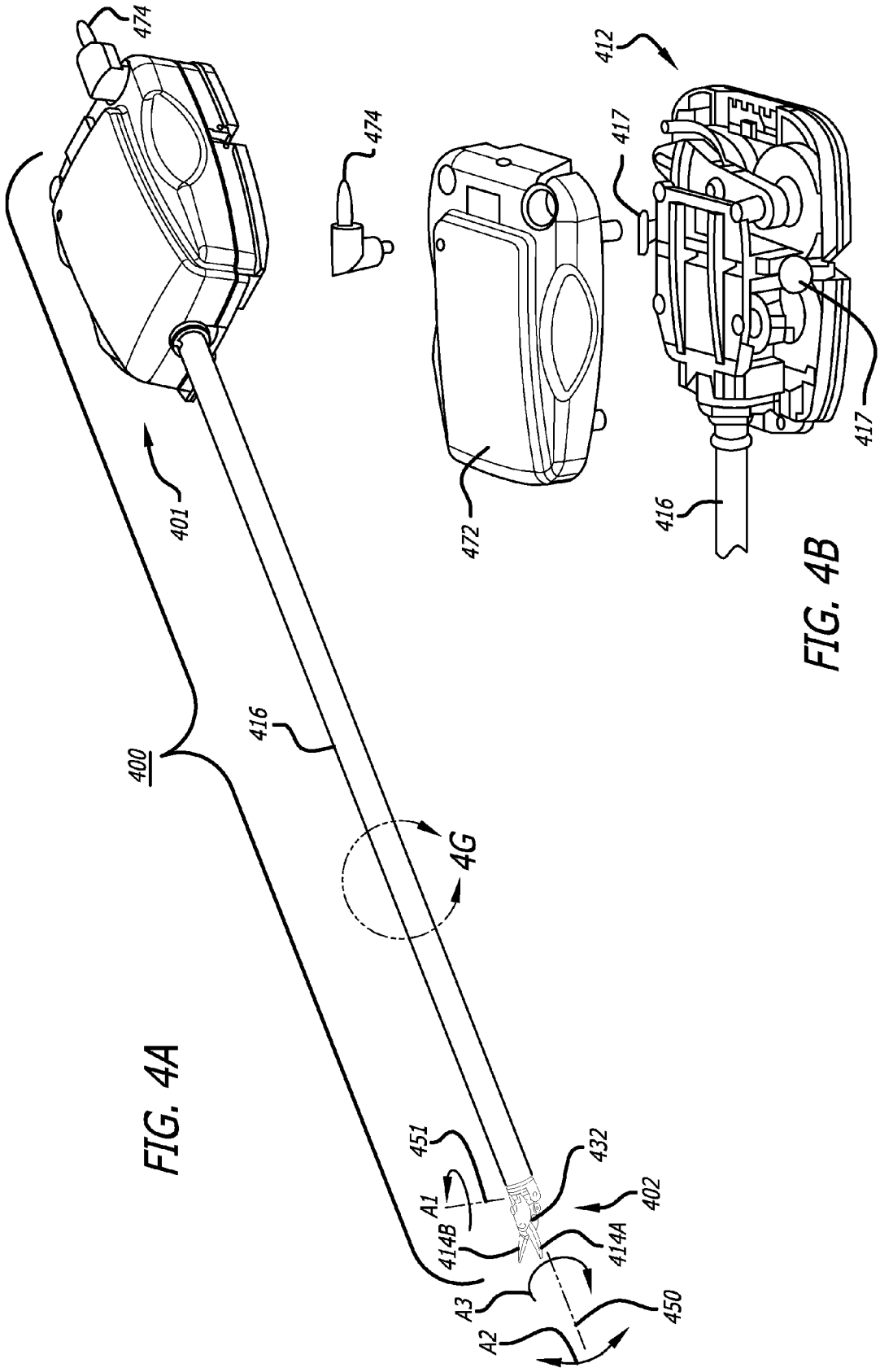
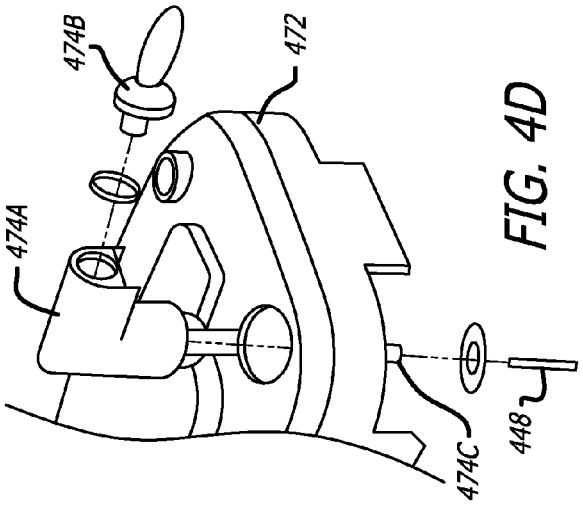

325
351
G
374
376
334a
334b
A
350A
350B
335a
I
335b
H
H
382
332d
378
368a
368b
ROLL MOTOR
ENCODER
F
370a
370b
370
380
384
330
390
388
J
386
392a
392b
398
394
362
396
S
N

FIG. 3C


474
401
400
416
4G
451
A1
414B
A3
A2
432
402
414A
450
FIG. 4A
474
472
412
417
417
416
FIG. 4B



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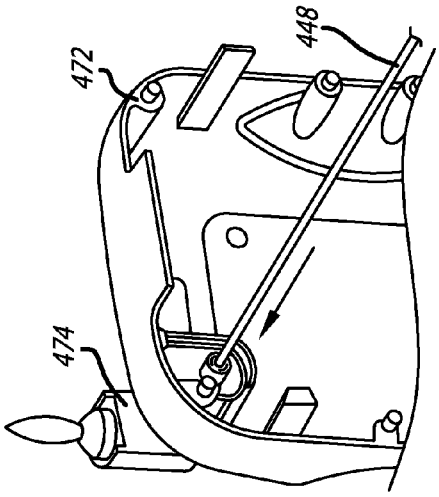


FIG. 4E

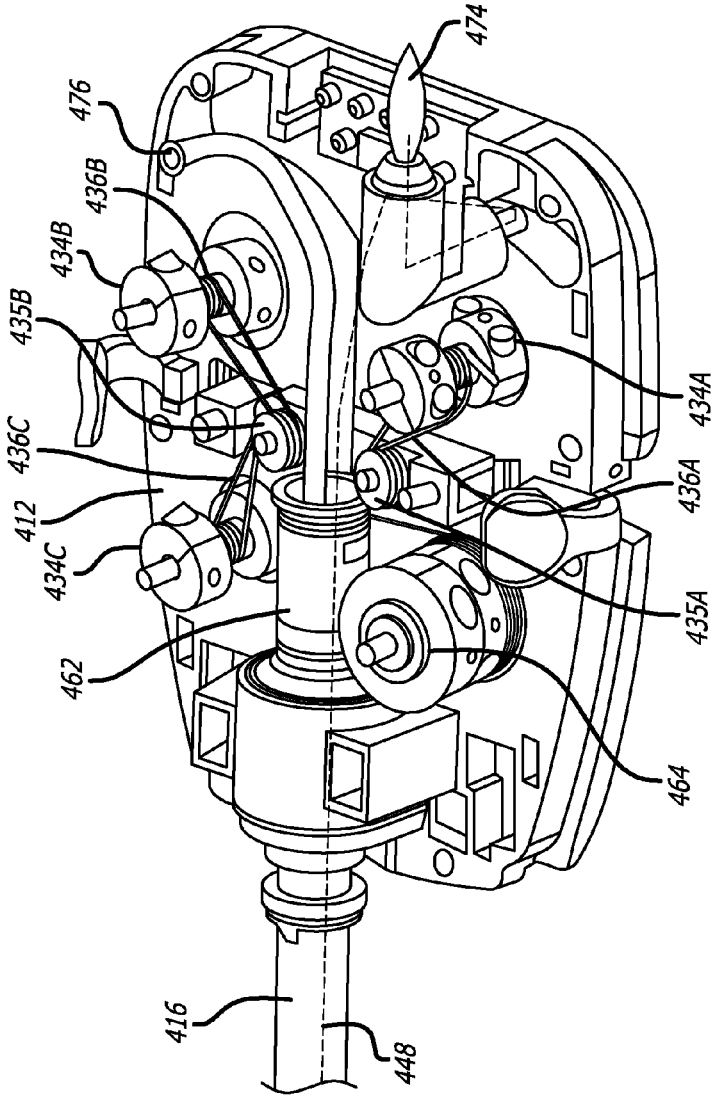


FIG. 4C

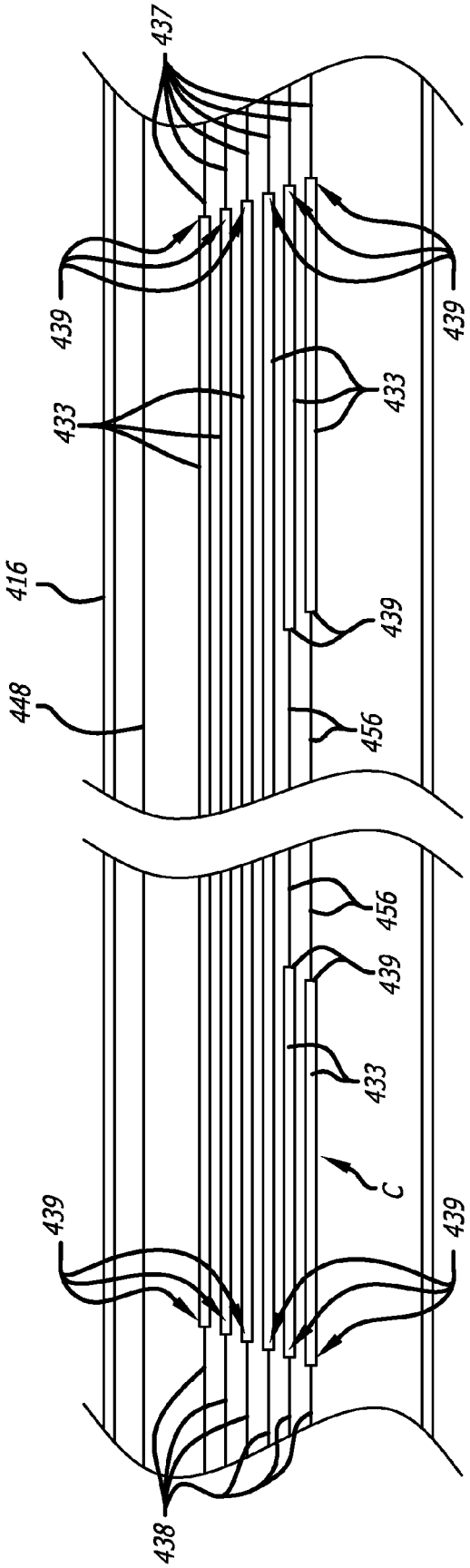
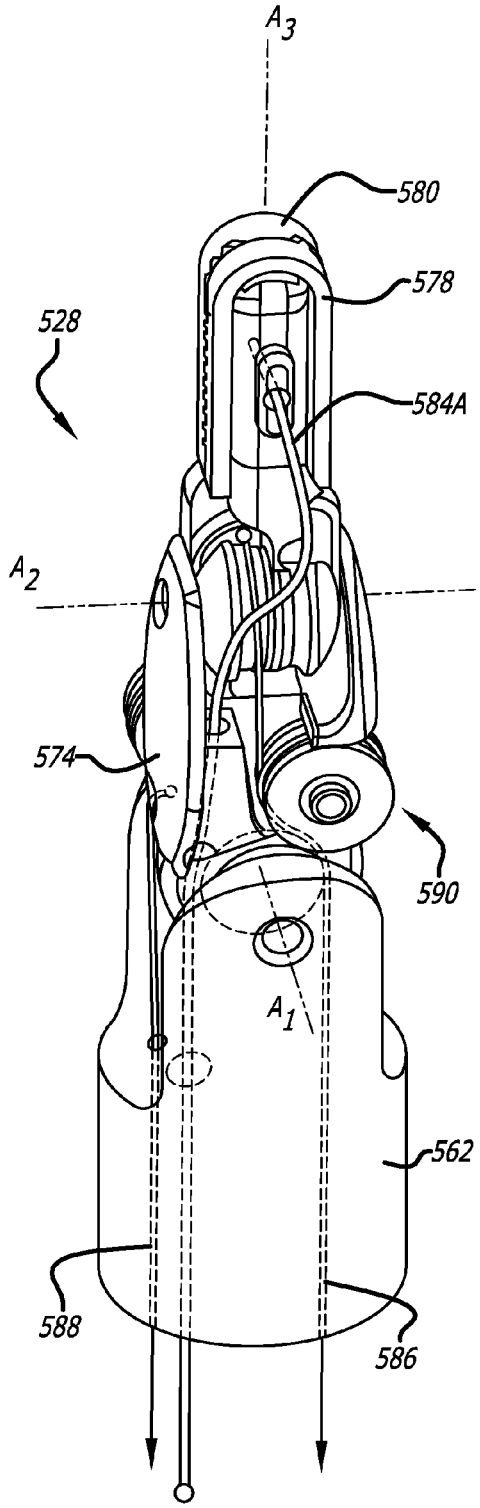


FIG. 4G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578
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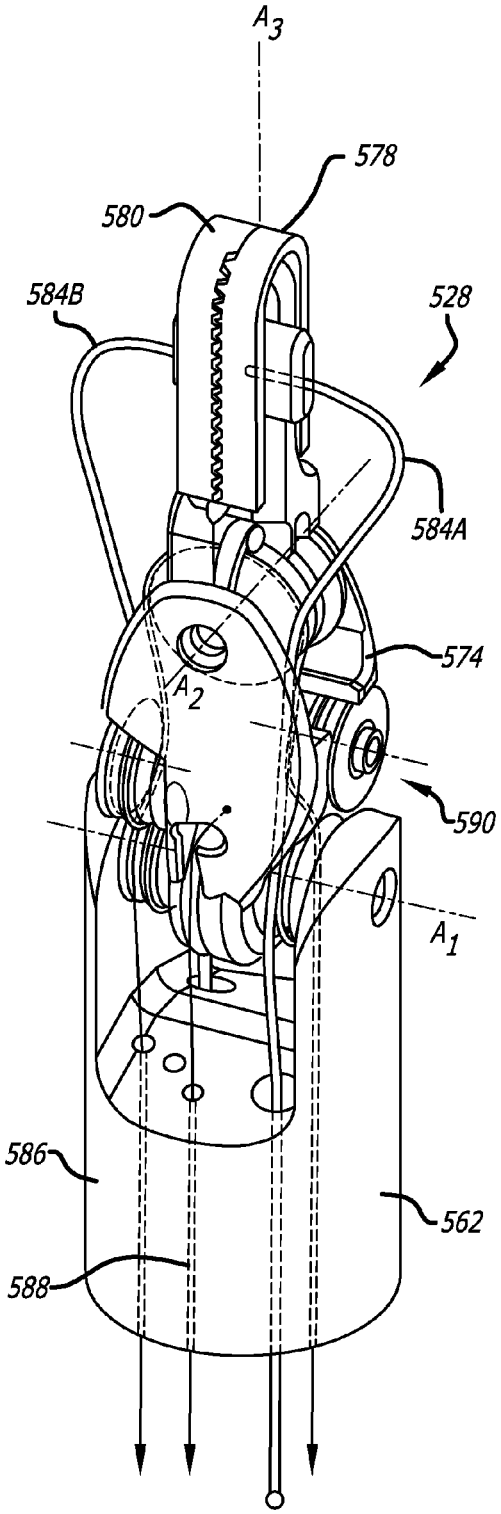
584A
A2
574
590
A1
562
588
586

FIG. 5A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A2
590
A1
586
562
588

FIG. 5B

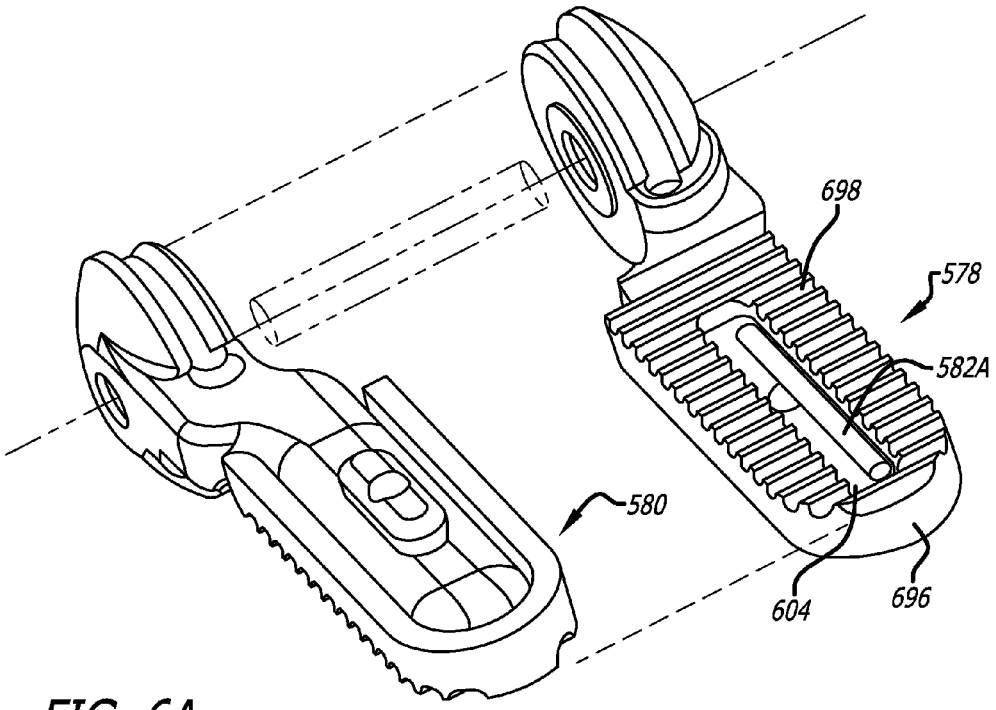


FIG. 6A

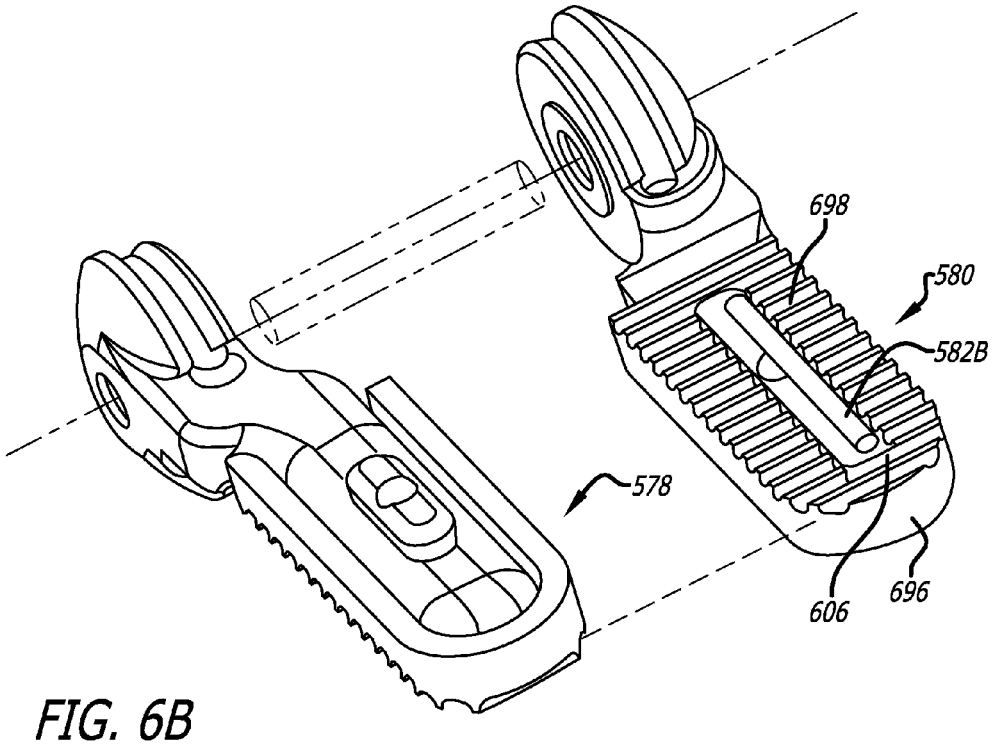


FIG. 6B

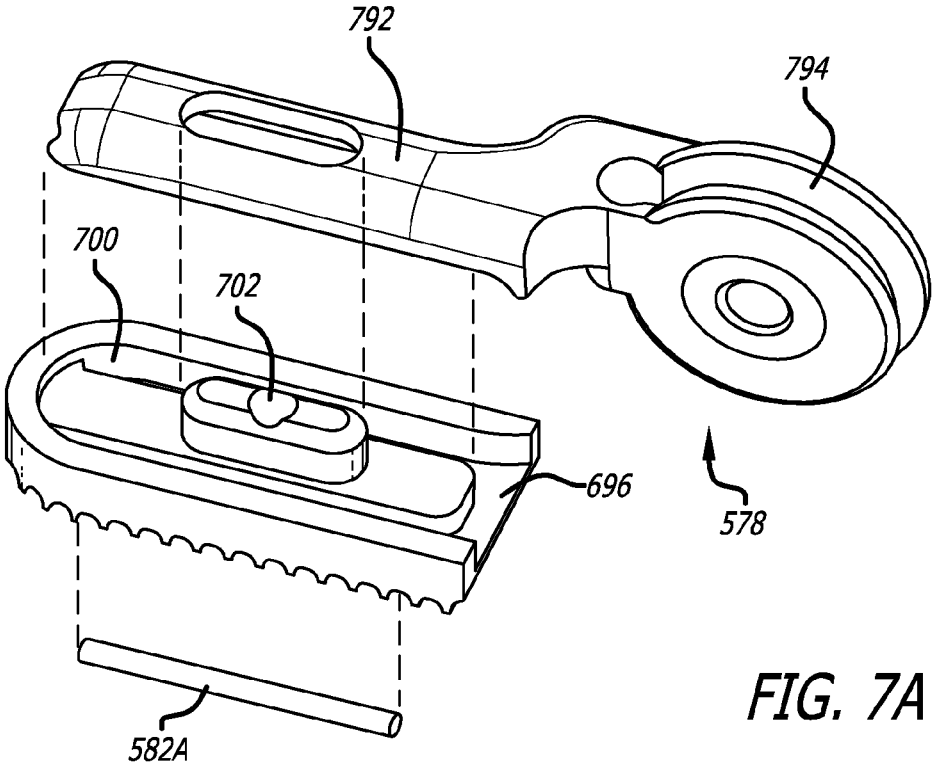


FIG. 7A

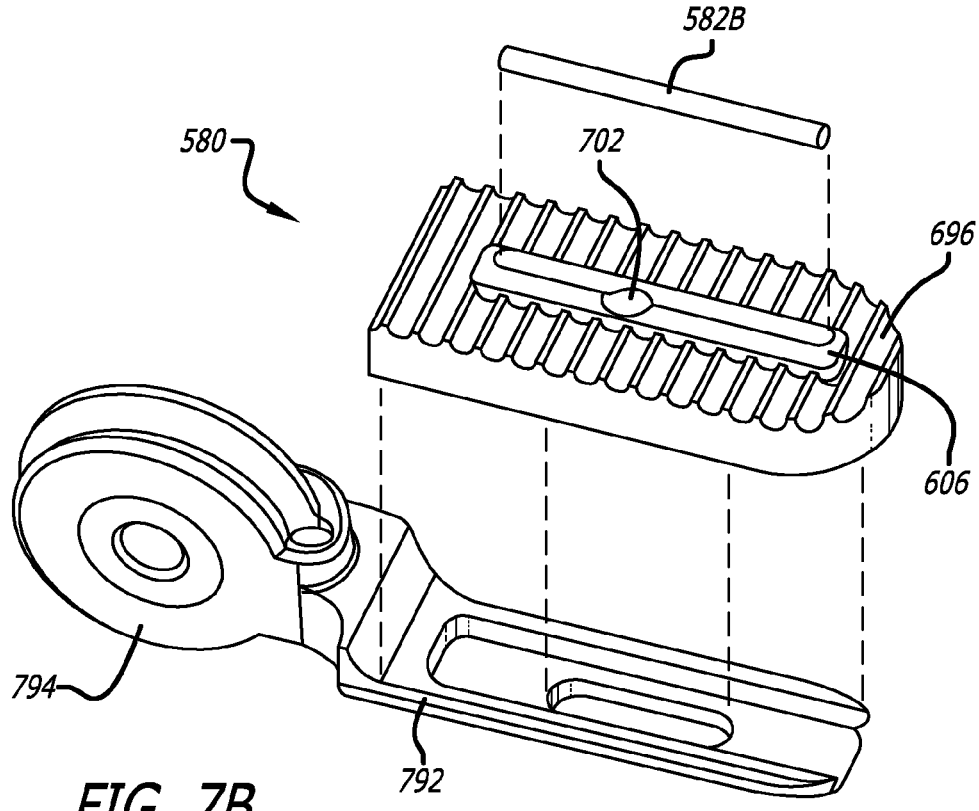
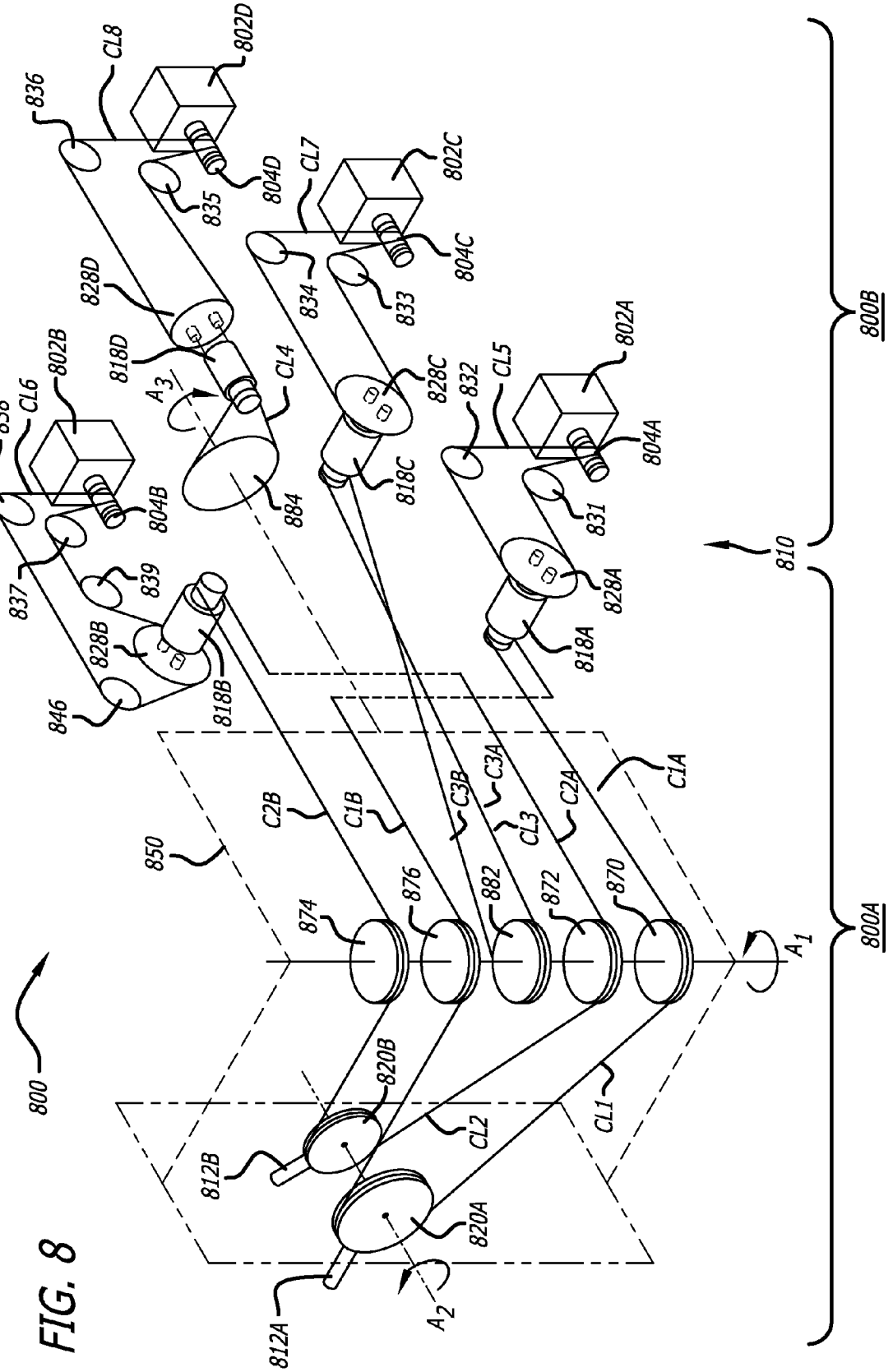


FIG. 7B


800
800A
800B
810
802A
802B
802C
802D
804A
804B
804C
804D
812A
812B
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818C
818D
820A
820B
828A
828B
828C
828D
831
832
833
834
835
836
837
838
839
846
850
870
872
874
876
882
884
A1
A2
A3
C1A
C1B
C2A
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C3A
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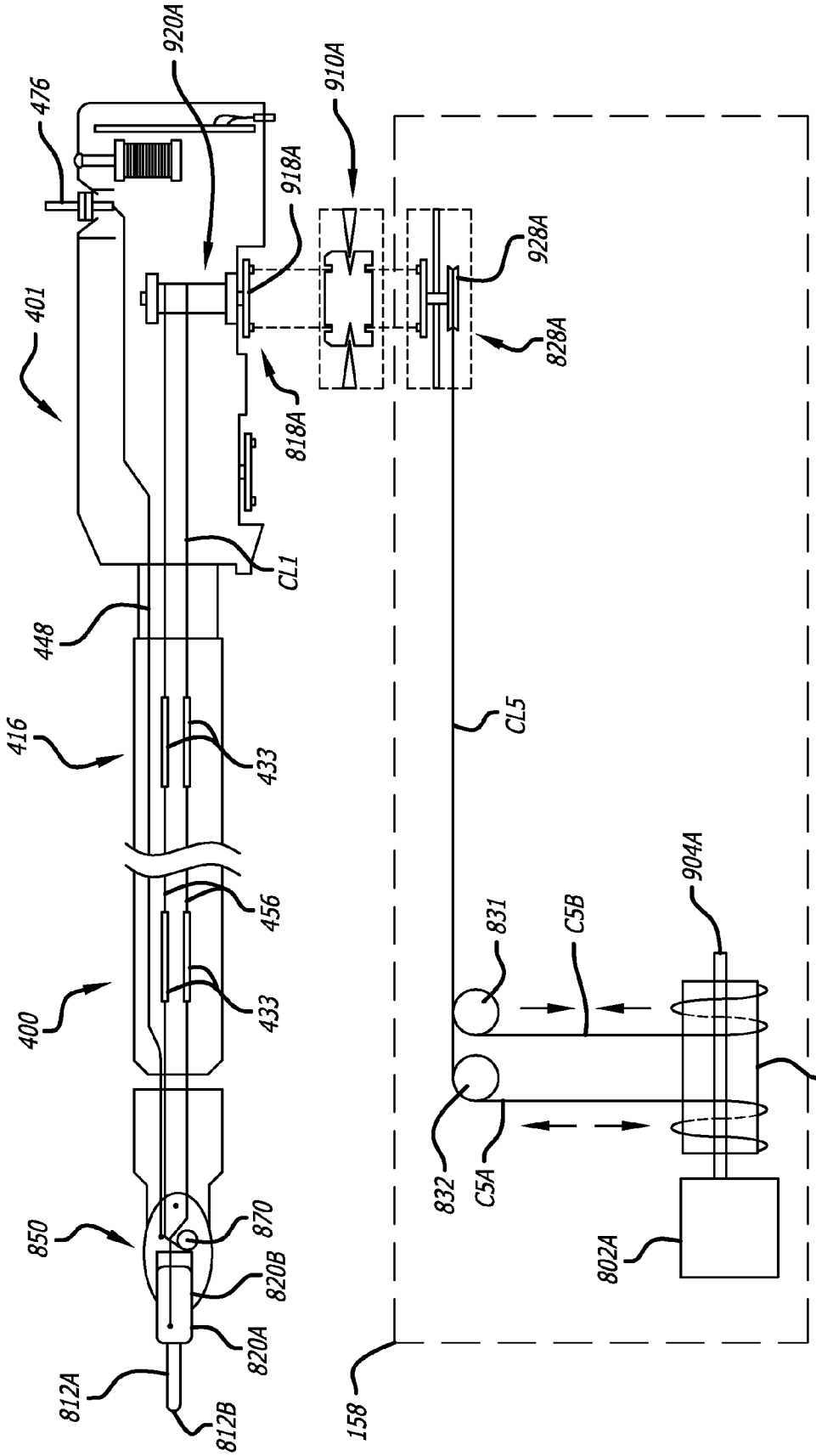
CL1
CL2
CL3
CL4
CL5
CL6
CL7
CL8

FIG. 8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820A
812A
812B
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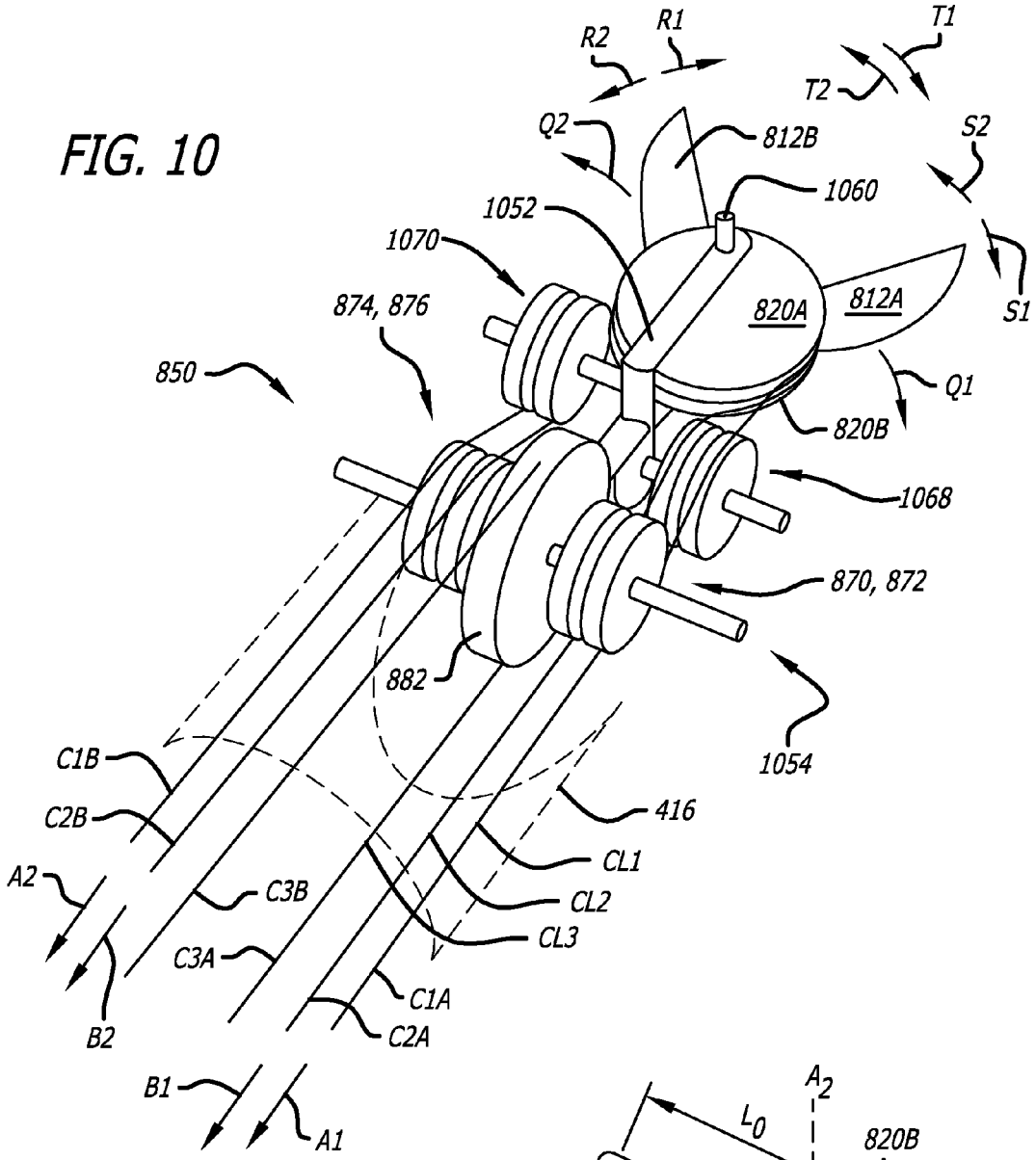
FIG. 9

FIG. 10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R1
T1
T2
Q2
812B
S2
1060
1052
1070
874, 876
820A
812A
S1
850
Q1
820B
1068
870, 872
882
1054
C1B
C2B
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A2
C3B
CL1
CL2
C3A
CL3
C1A
B2
C2A
B1
A1

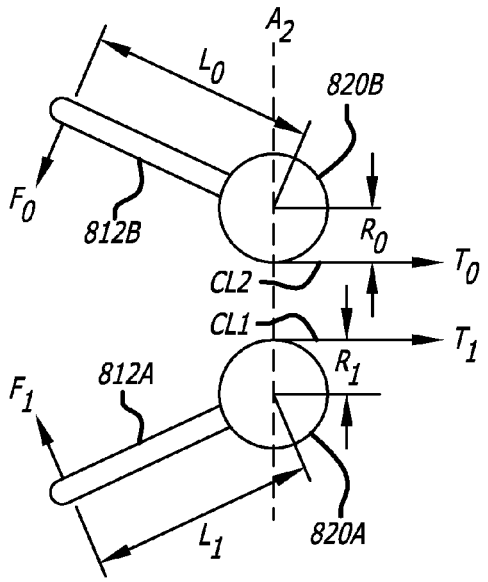

A_2
L_0
820B
F_0
812B
R_0
T_0
CL2
CL1
T_1
R_1
F_1
812A
L_1
820A

FIG. 11

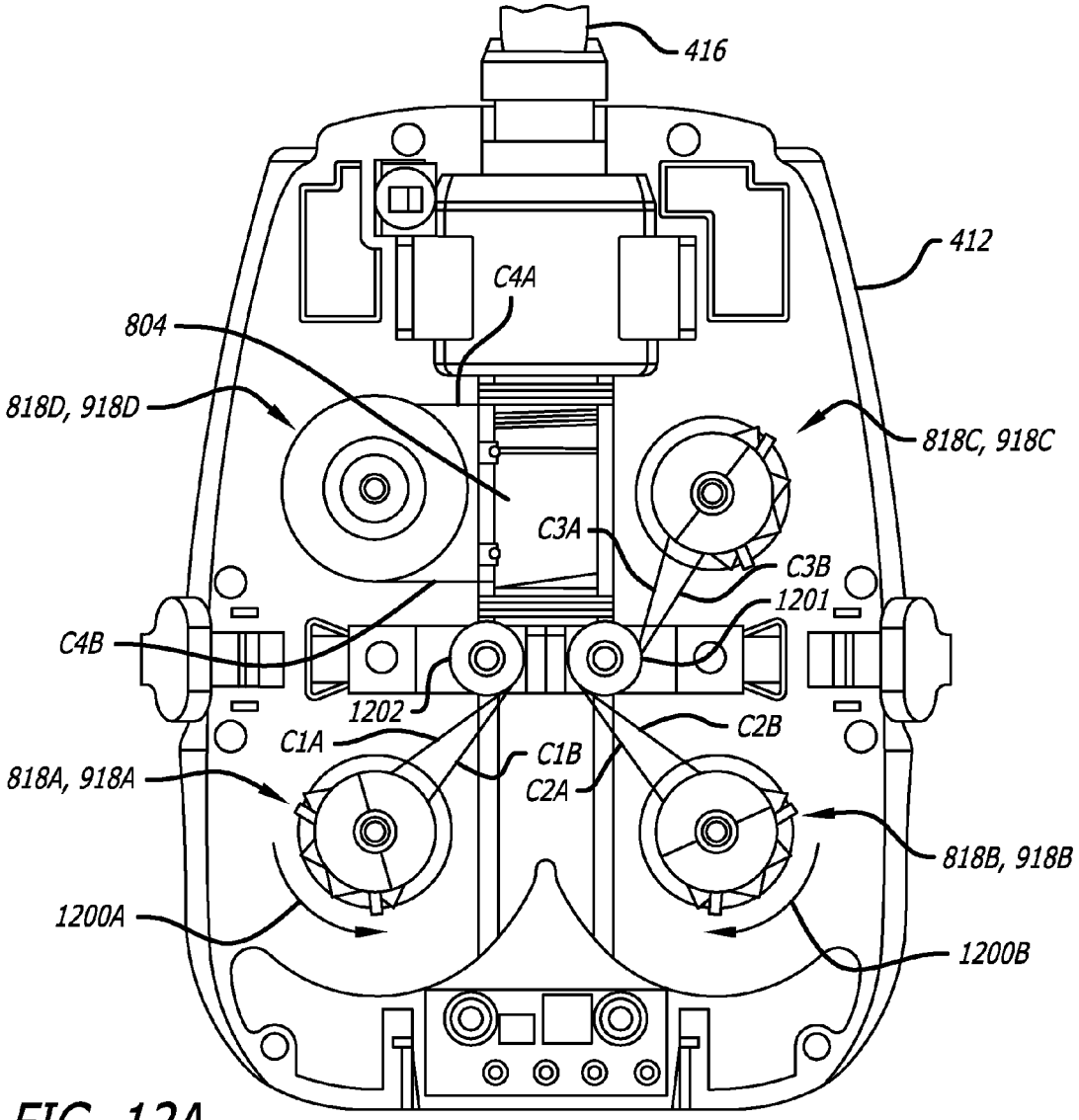


FIG. 12A

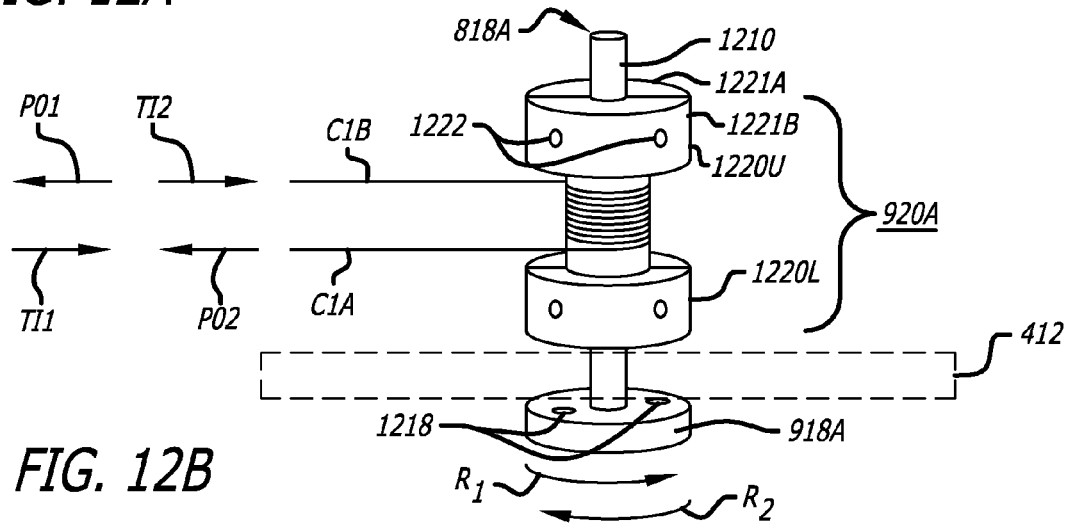


FIG. 12B

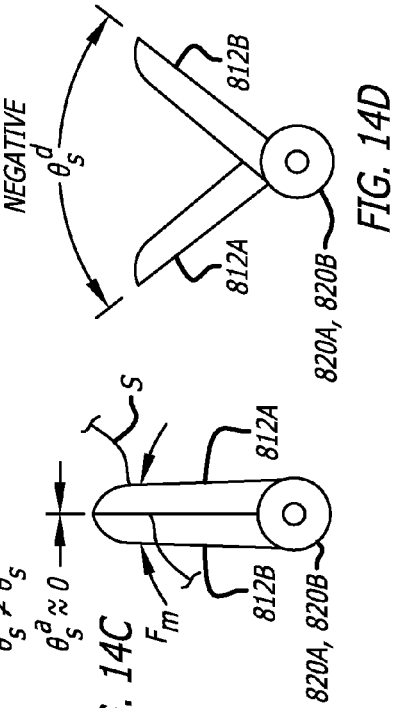


FIG. 14D

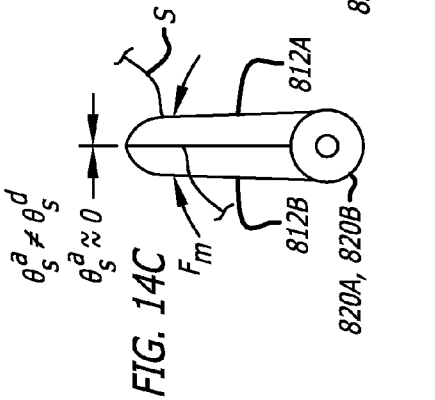


FIG. 14C

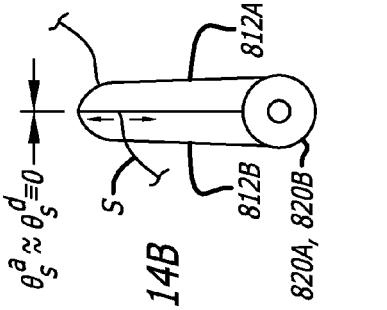


FIG. 14B

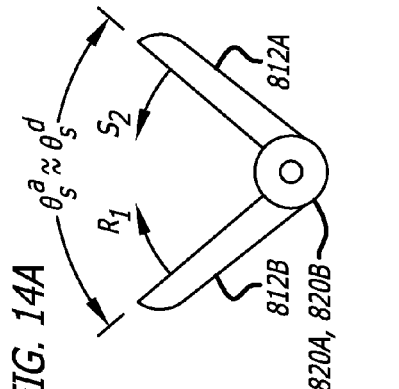


FIG. 14A

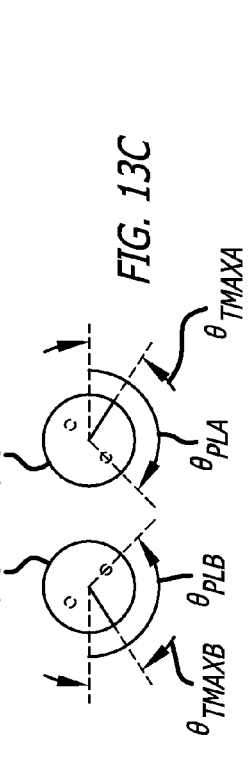


FIG. 13C

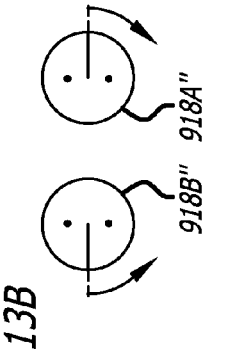


FIG. 13B

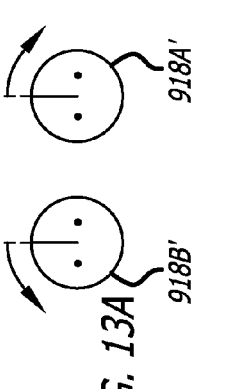


FIG. 13A

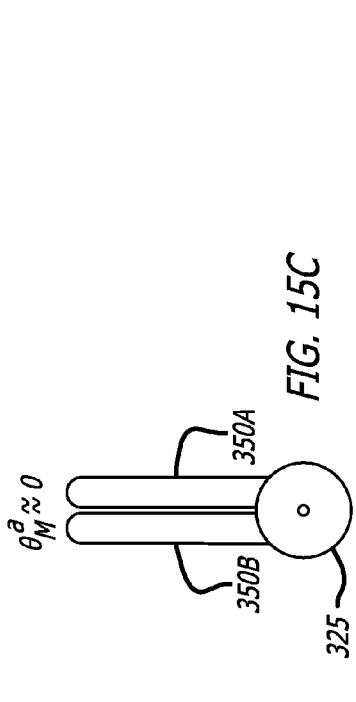


FIG. 15C

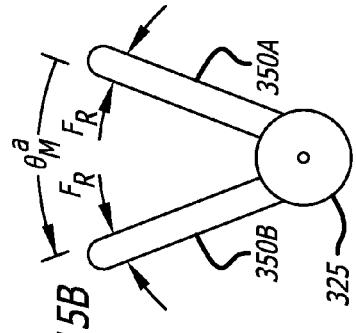


FIG. 15B

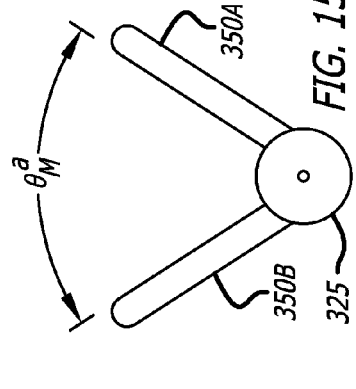


FIG. 15A

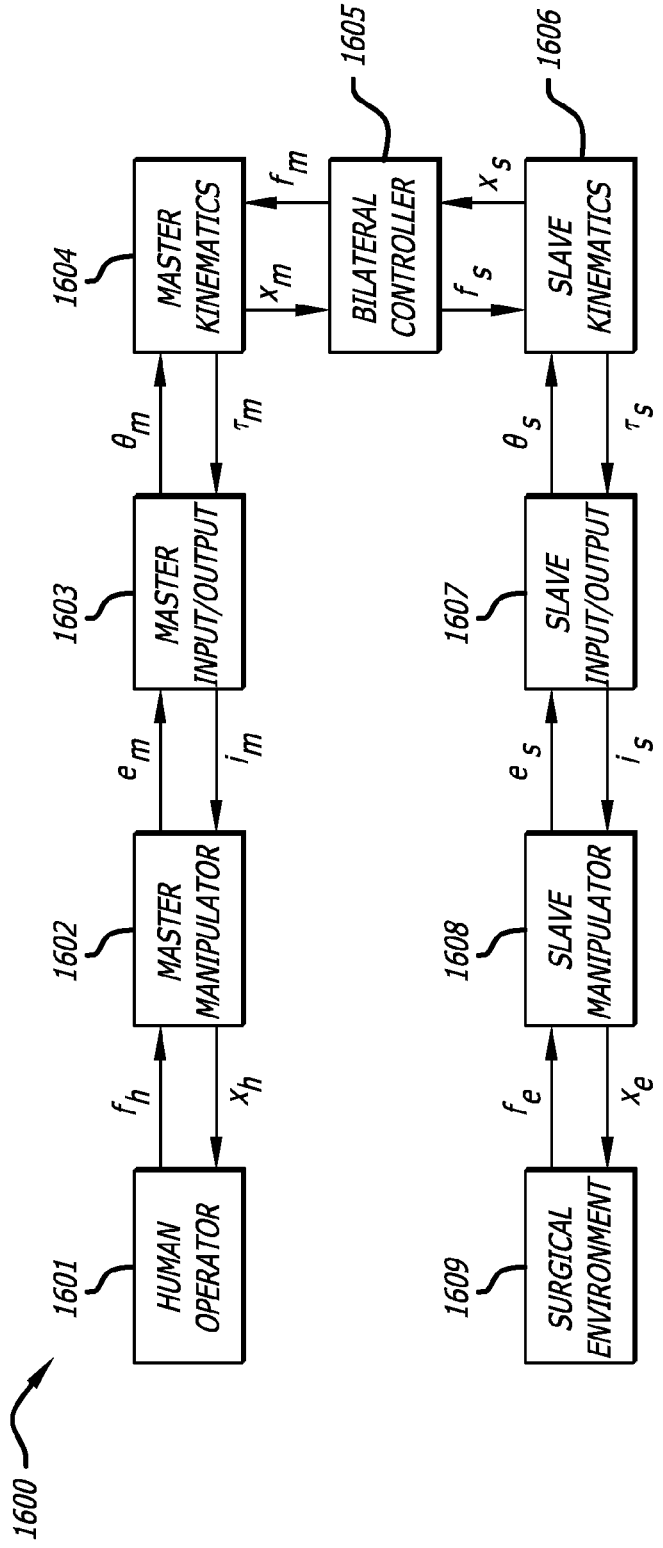


FIG. 16A

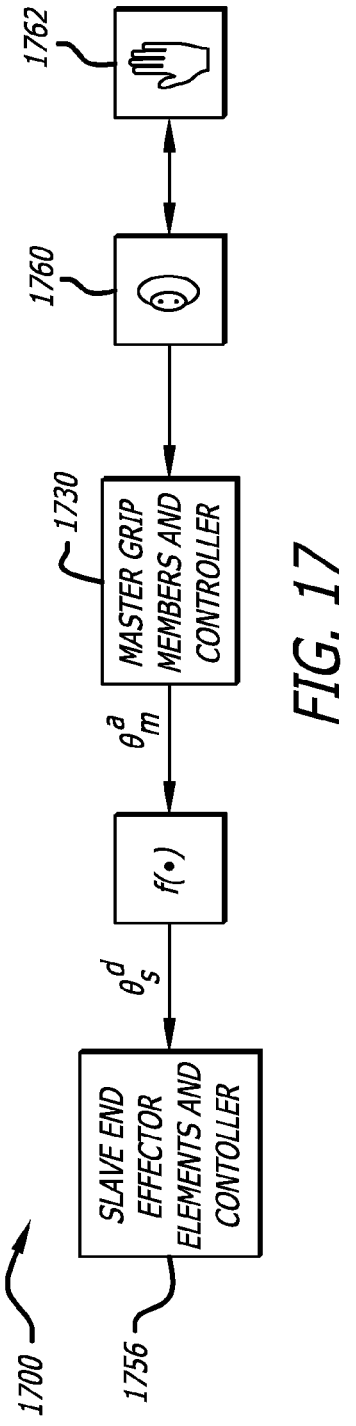


FIG. 17

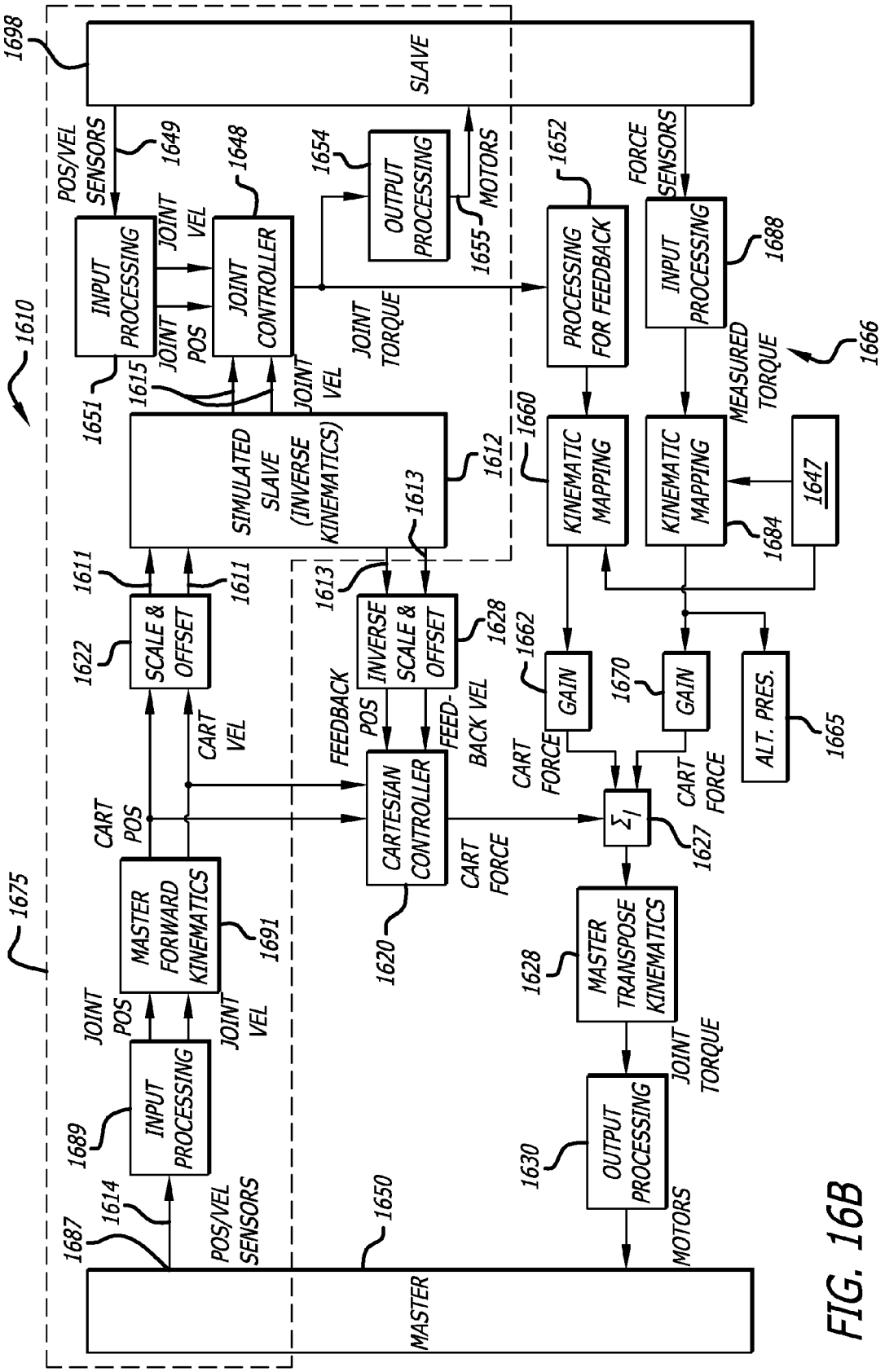

1698
SLAVE
POS/VEL SENSORS
1649
1648
1654
OUTPUT PROCESSING
1655
MOTORS
1652
FORCE SENSORS
INPUT PROCESSING
JOINT VEL
JOINT CONTROLLER
JOINT TORQUE
PROCESSING FOR FEEDBACK
INPUT PROCESSING
1688
1610
1651
1615
JOINT POS
JOINT VEL
MEASURED TORQUE
1666
SIMULATED SLAVE (INVERSE KINEMATICS)
1612
1613
1660
KINEMATIC MAPPING
KINEMATIC MAPPING
1647
1684
1611
1611
1613
SCALE & OFFSET
INVERSE SCALE & OFFSET
1628
1622
1662
GAIN
1670
GAIN
ALT. PRES.
1665
FEEDBACK POS
FEED-BACK VEL
CART VEL
CART POS
CARTESIAN CONTROLLER
CART FORCE
CART FORCE
CART FORCE
Σ
1627
1675
MASTER FORWARD KINEMATICS
1691
1620
1628
MASTER TRANSPOSE KINEMATICS
JOINT POS
JOINT VEL
JOINT TORQUE
INPUT PROCESSING
1689
1630
OUTPUT PROCESSING
1614
1687
POS/VEL SENSORS
1650
MOTORS
MASTER

FIG. 16B

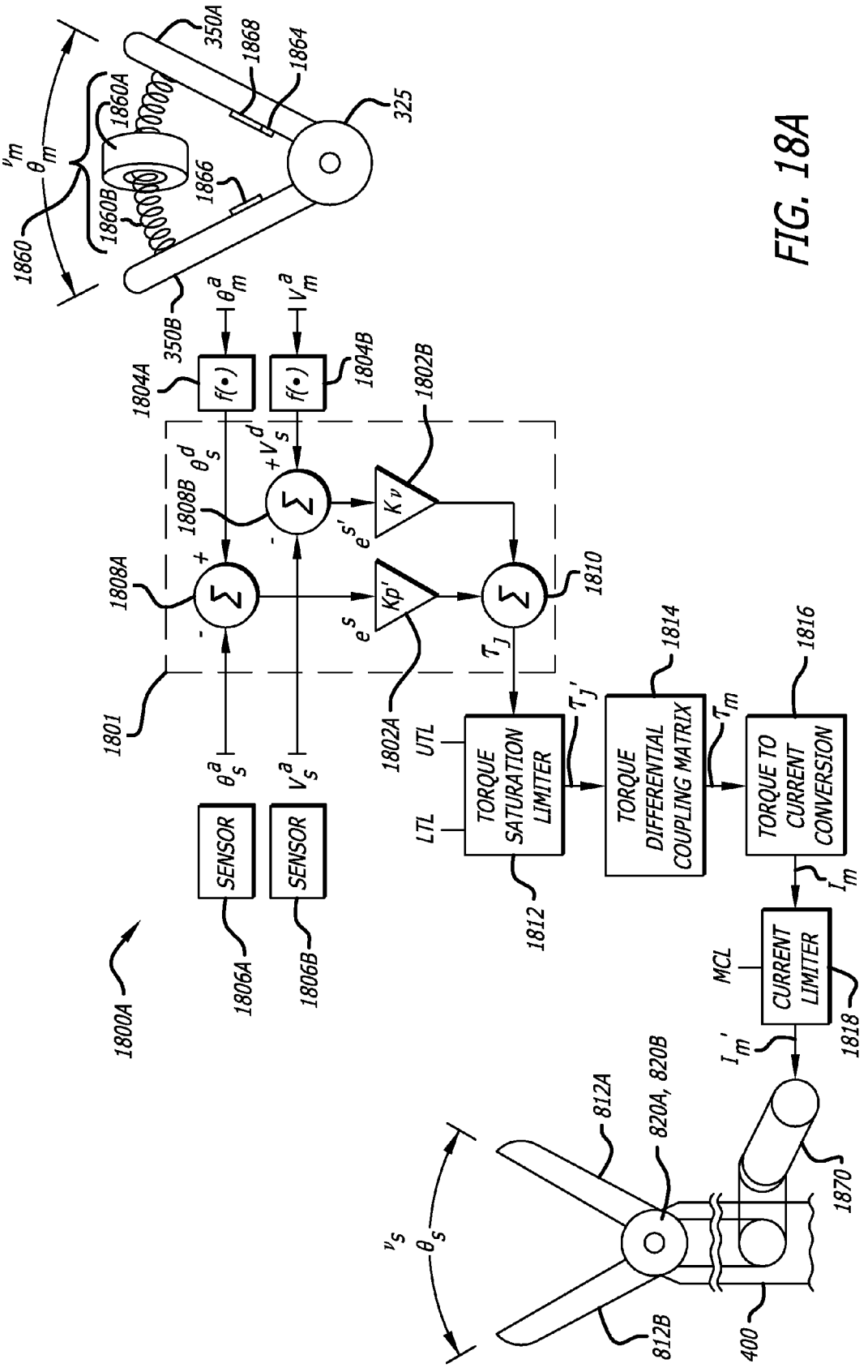

1860
1860A
1860B
1866
1868
1864
350A
325
350B
1804A
1804B
f(•)
1808A
1808B
1801
1802A
1802B
1810
Kv
Kp'
1812
TORQUE SATURATION LIMITER
UTL
LTL
1814
TORQUE DIFFERENTIAL COUPLING MATRIX
1816
TORQUE TO CURRENT CONVERSION
1818
CURRENT LIMITER
MCL
SENSOR
1806A
1806B
1800A
812A
812B
820A, 820B
1870
400

FIG. 18A

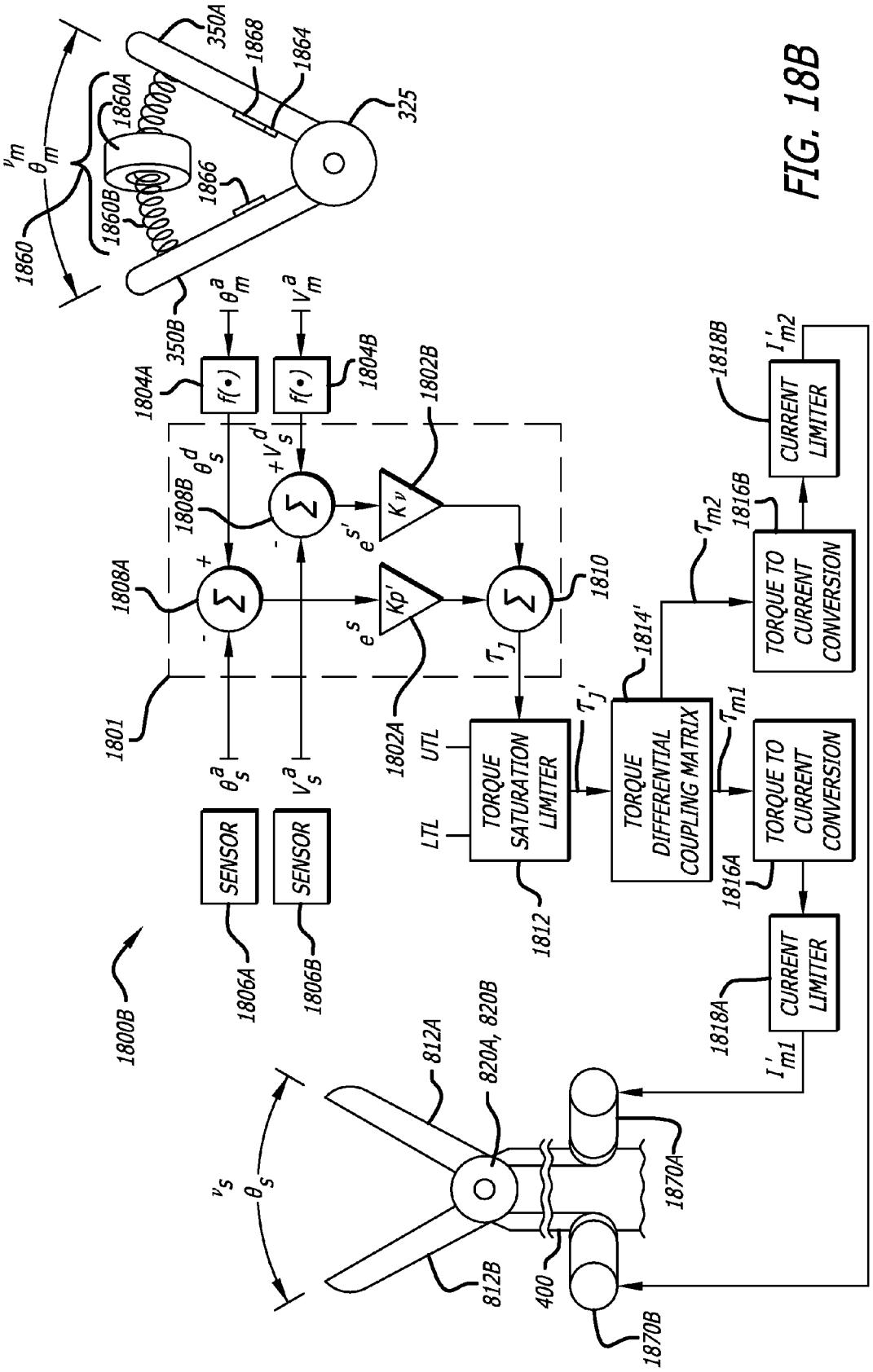

1860
1860A
1860B
1866
1868
1864
350A
325
350B
1804A
1804B
f(•)
1802B
1808B
1808A
1801
1802A
Kv
Kp'
1810
1812
1814'
1816A
1816B
1818A
1818B
1806A
1806B
SENSOR
TORQUE SATURATION LIMITER
TORQUE DIFFERENTIAL COUPLING MATRIX
TORQUE TO CURRENT CONVERSION
CURRENT LIMITER
UTL
LTL
1800B
812A
812B
820A, 820B
400
1870A
1870B

FIG. 18B

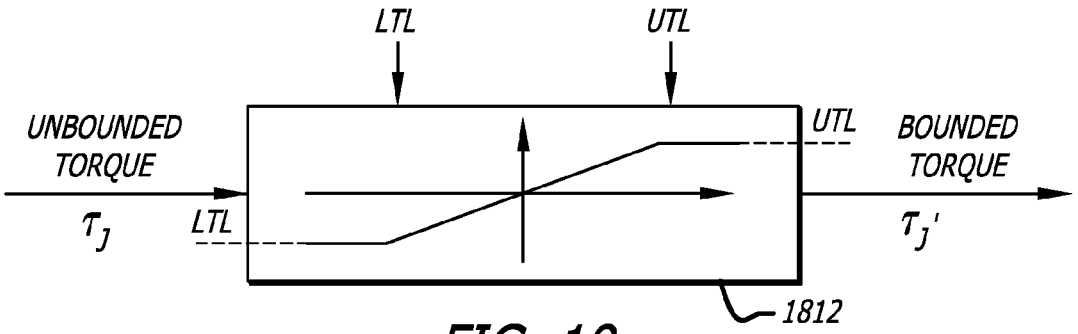


FIG. 19

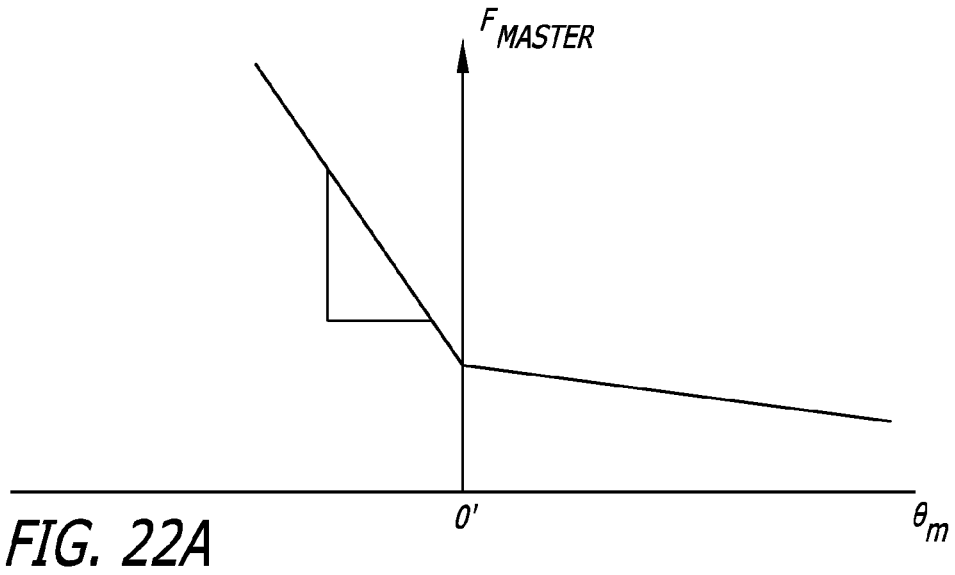


FIG. 22A

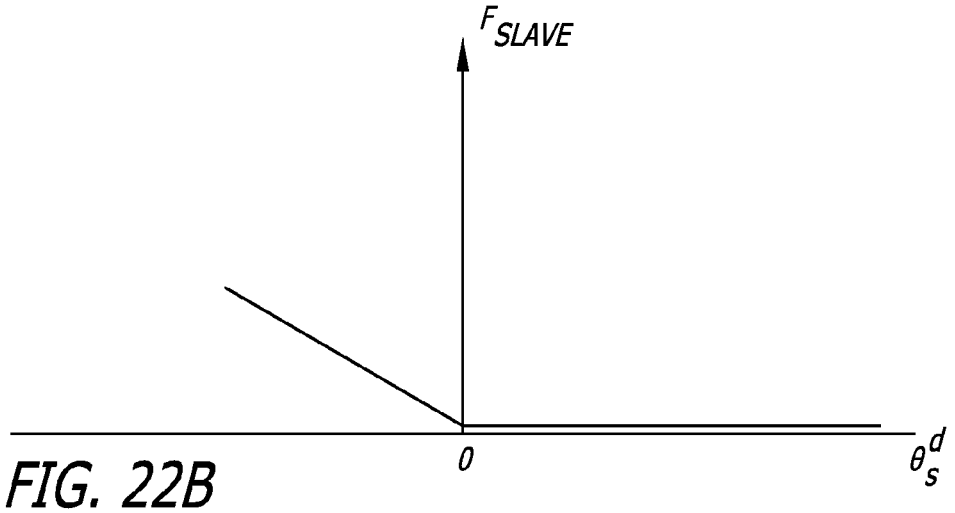


FIG. 22B

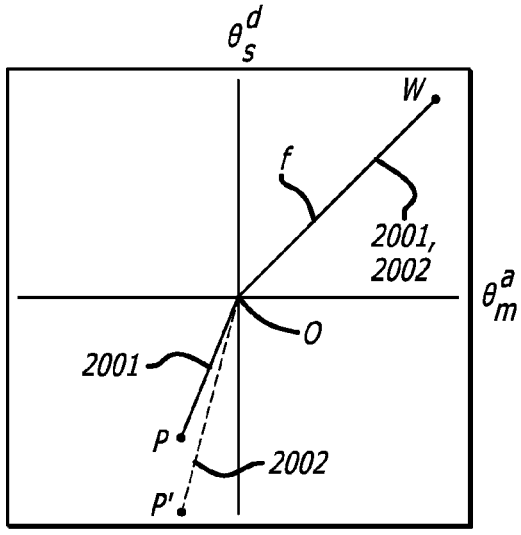


FIG. 20

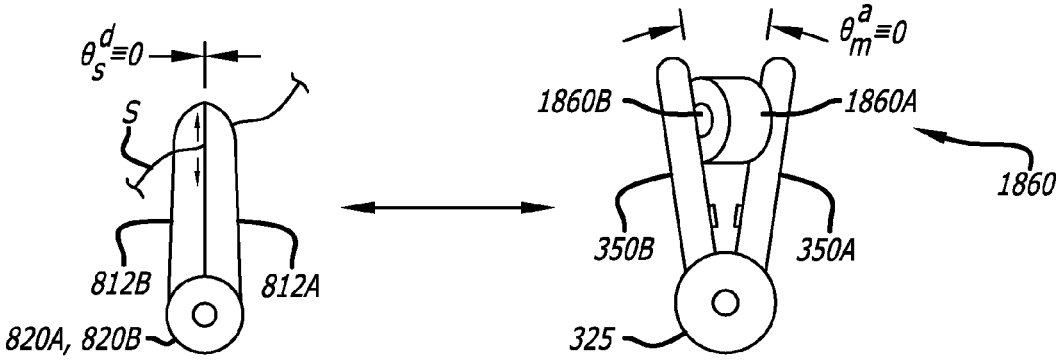


FIG. 21A

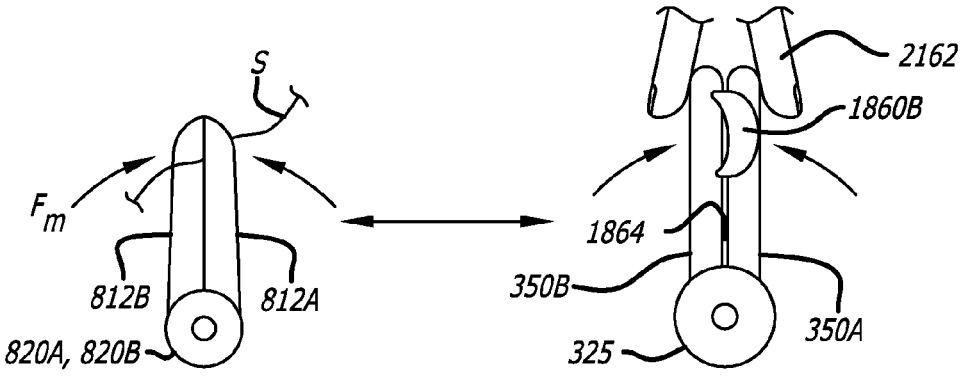


FIG. 21B

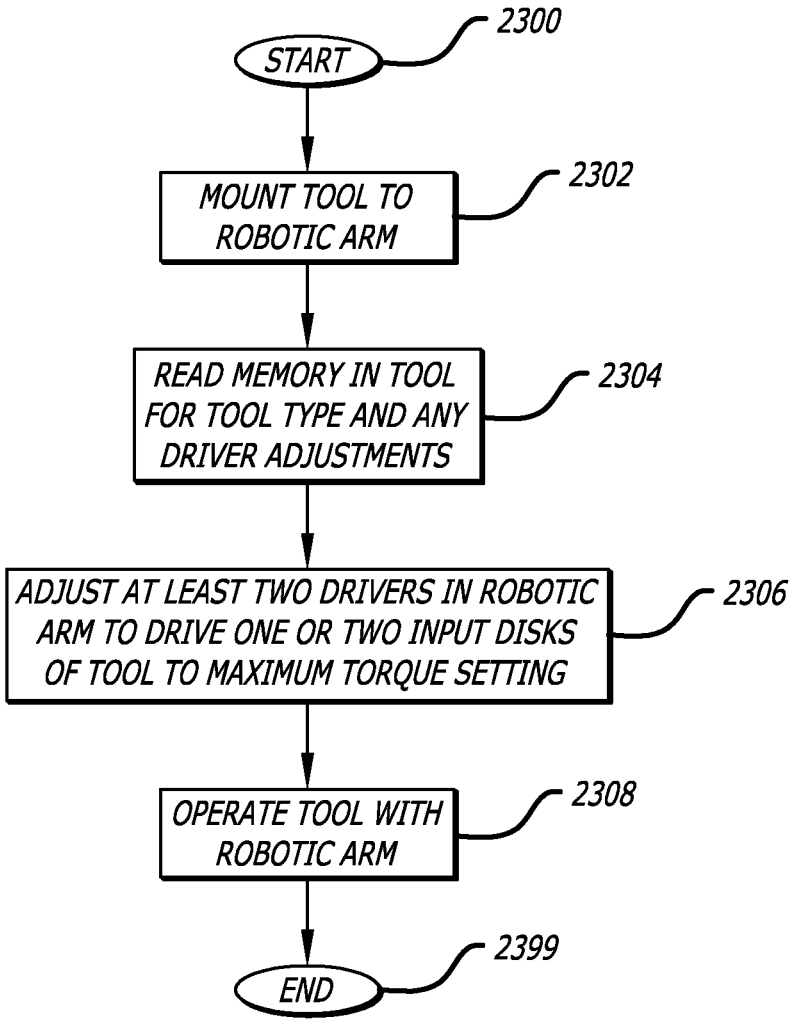

2300
START
MOUNT TOOL TO ROBOTIC ARM
2302
READ MEMORY IN TOOL FOR TOOL TYPE AND ANY DRIVER ADJUSTMENTS
2304
ADJUST AT LEAST TWO DRIVERS IN ROBOTIC ARM TO DRIVE ONE OR TWO INPUT DISKS OF TOOL TO MAXIMUM TORQUE SETTING
2306
OPERATE TOOL WITH ROBOTIC ARM
2308
END
2399

FIG. 23

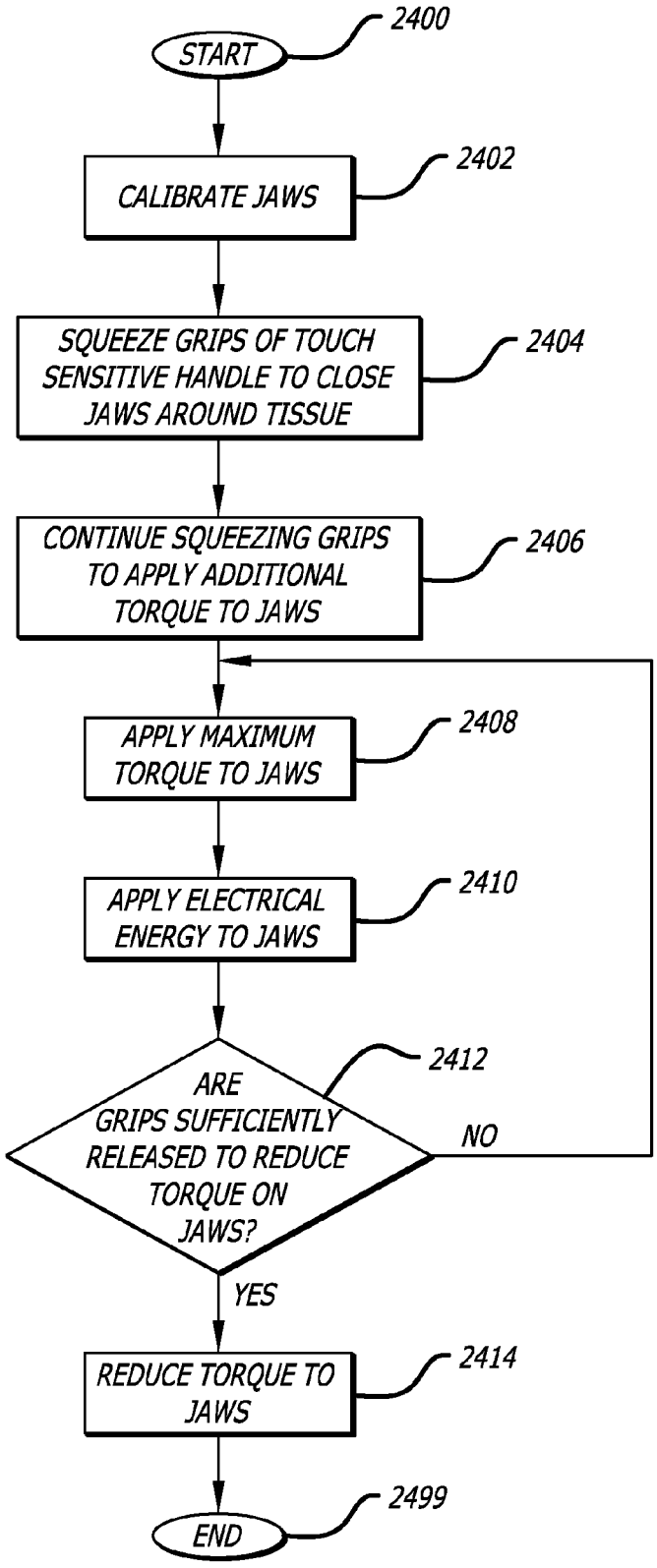

2400
START
2402
CALIBRATE JAWS
2404
SQUEEZE GRIPS OF TOUCH SENSITIVE HANDLE TO CLOSE JAWS AROUND TISSUE
2406
CONTINUE SQUEEZING GRIPS TO APPLY ADDITIONAL TORQUE TO JAWS
2408
APPLY MAXIMUM TORQUE TO JAWS
2410
APPLY ELECTRICAL ENERGY TO JAWS
2412
ARE GRIPS SUFFICIENTLY RELEASED TO REDUCE TORQUE ON JAWS?
NO
YES
2414
REDUCE TORQUE TO JAWS
2499
END

FIG. 24

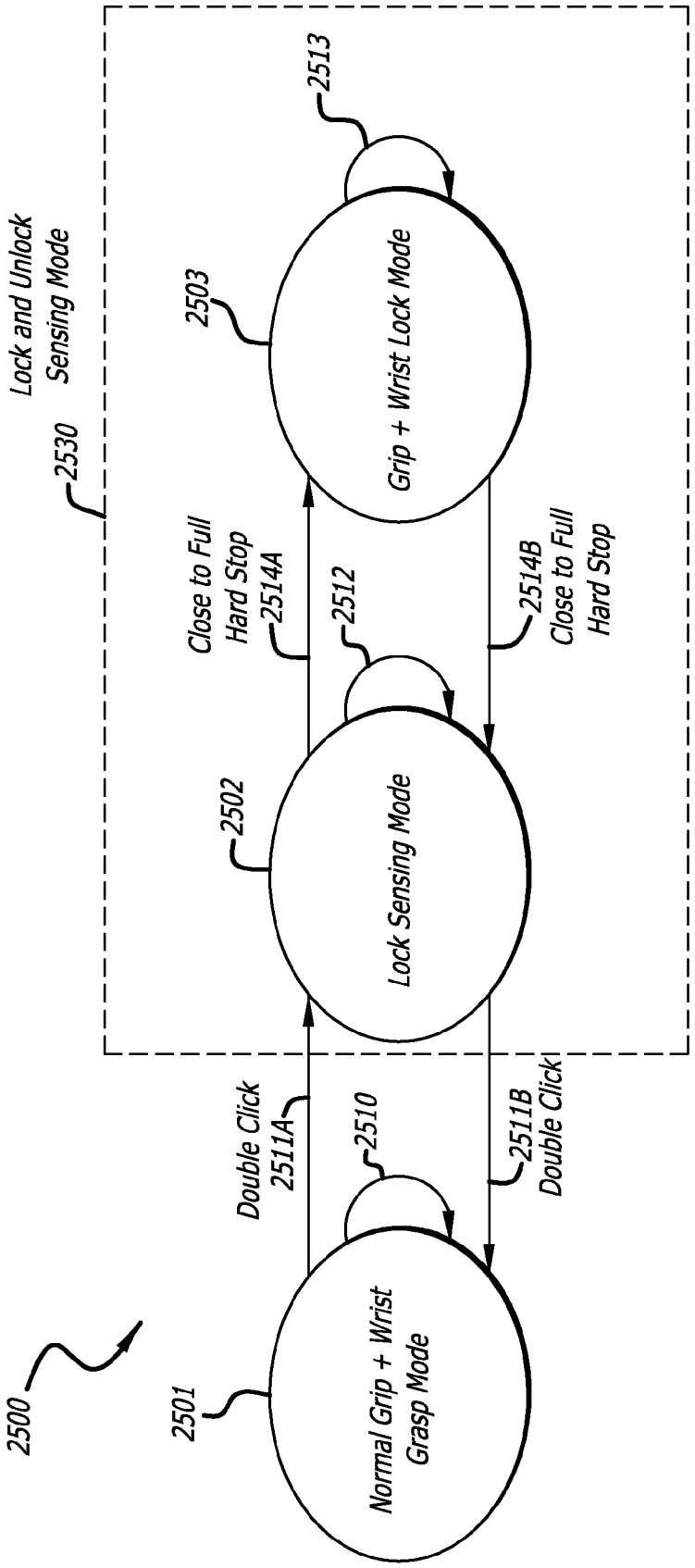


FIG. 25A

State Diagram for Locked Wrist Mode and Locked Grip Mode

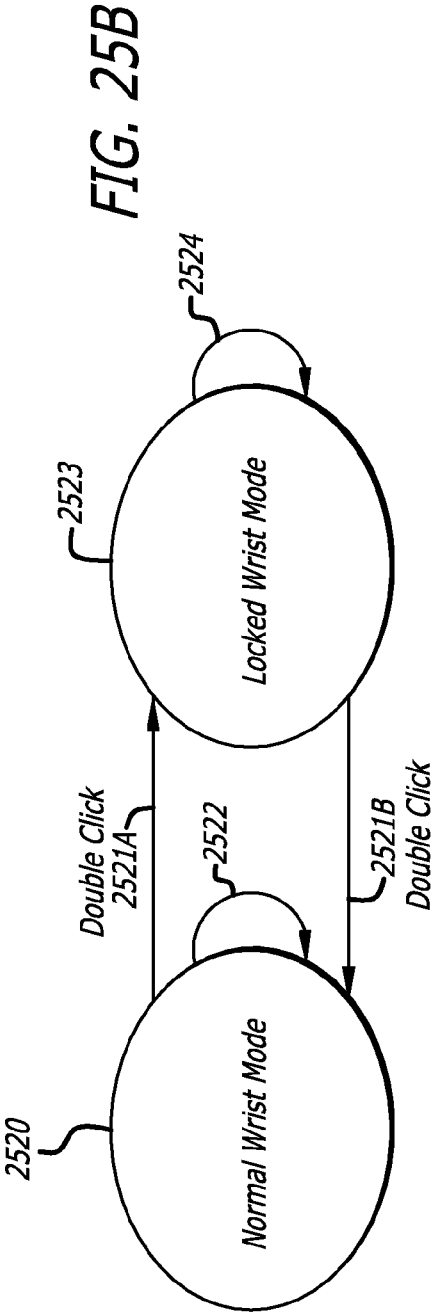


FIG. 25B

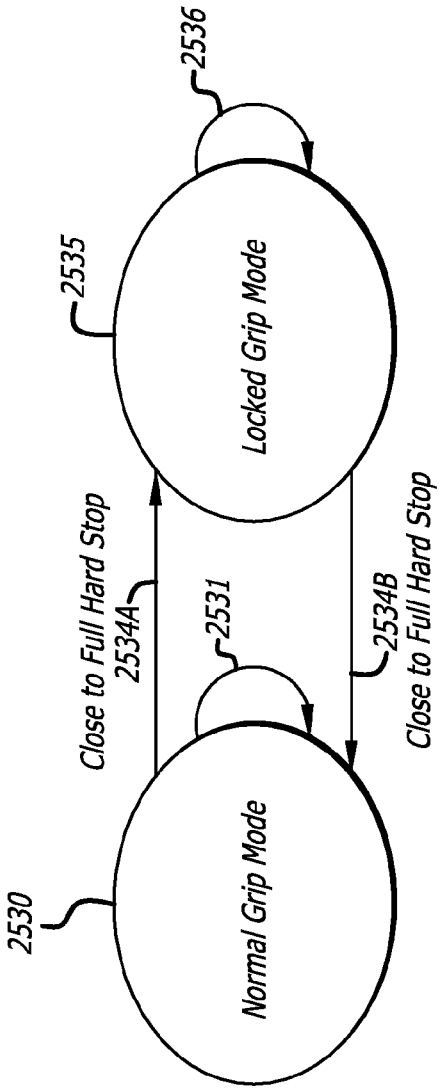


FIG. 25C

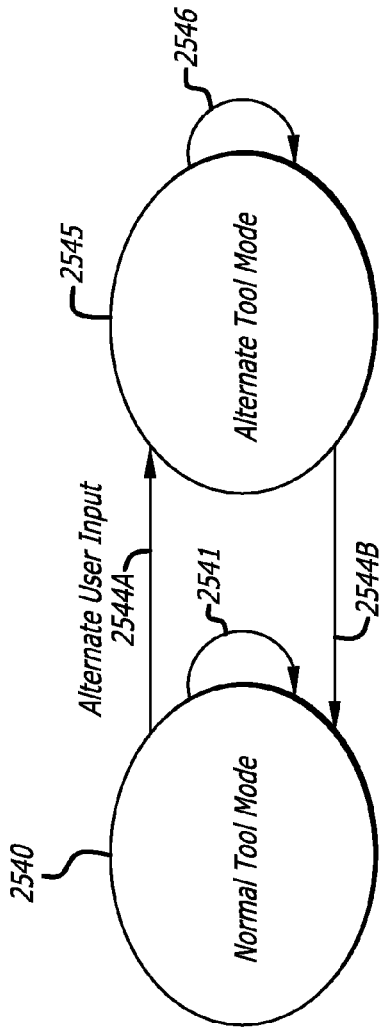


FIG. 25D

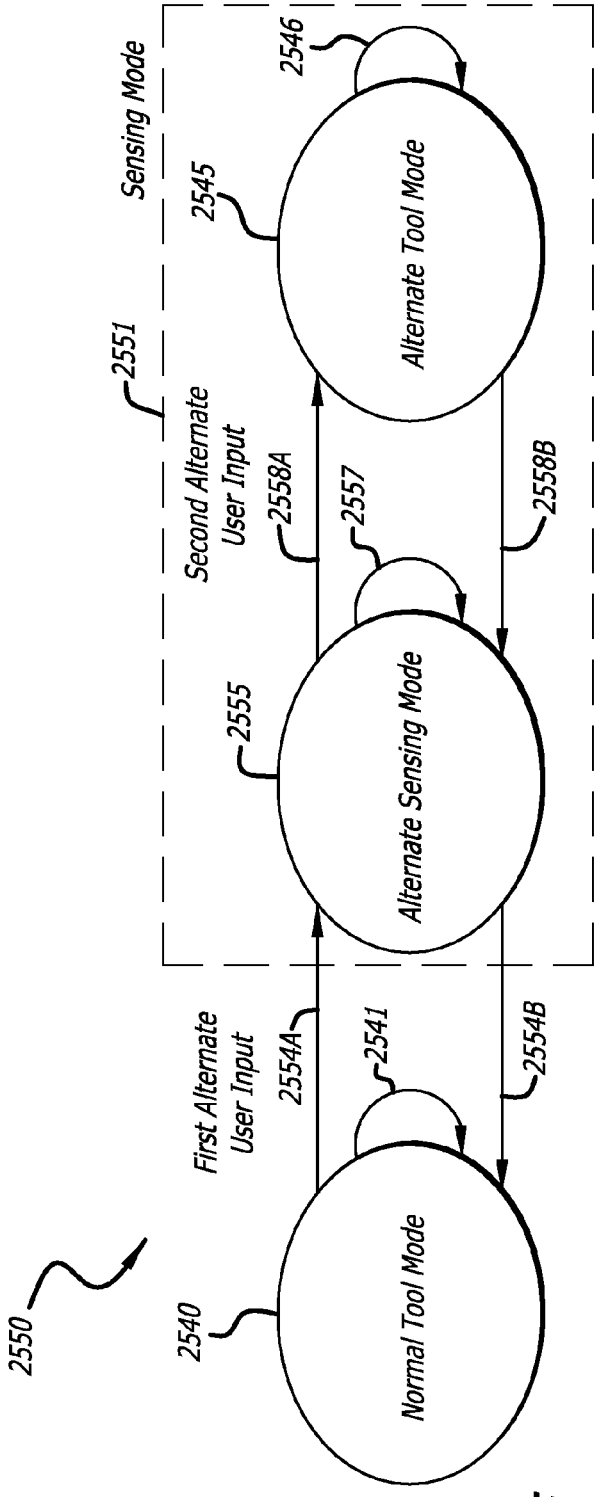


FIG. 25E

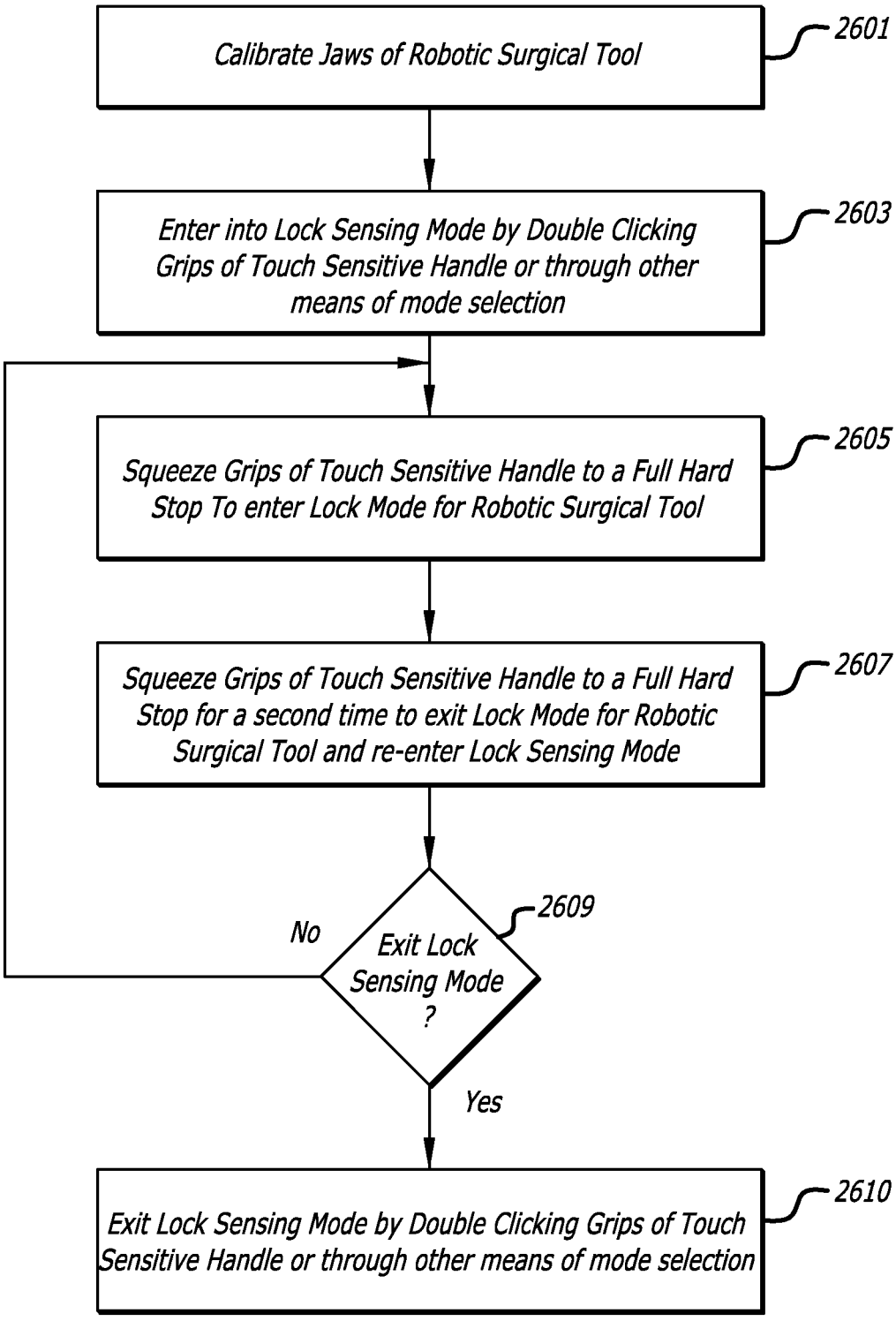

Calibrate Jaws of Robotic Surgical Tool
2601
Enter into Lock Sensing Mode by Double Clicking Grips of Touch Sensitive Handle or through other means of mode selection
2603
Squeeze Grips of Touch Sensitive Handle to a Full Hard Stop To enter Lock Mode for Robotic Surgical Tool
2605
Squeeze Grips of Touch Sensitive Handle to a Full Hard Stop for a second time to exit Lock Mode for Robotic Surgical Tool and re-enter Lock Sensing Mode
2607
Exit Lock Sensing Mode ?
2609
No
Yes
Exit Lock Sensing Mode by Double Clicking Grips of Touch Sensitive Handle or through other means of mode selection
2610

FIG. 26A

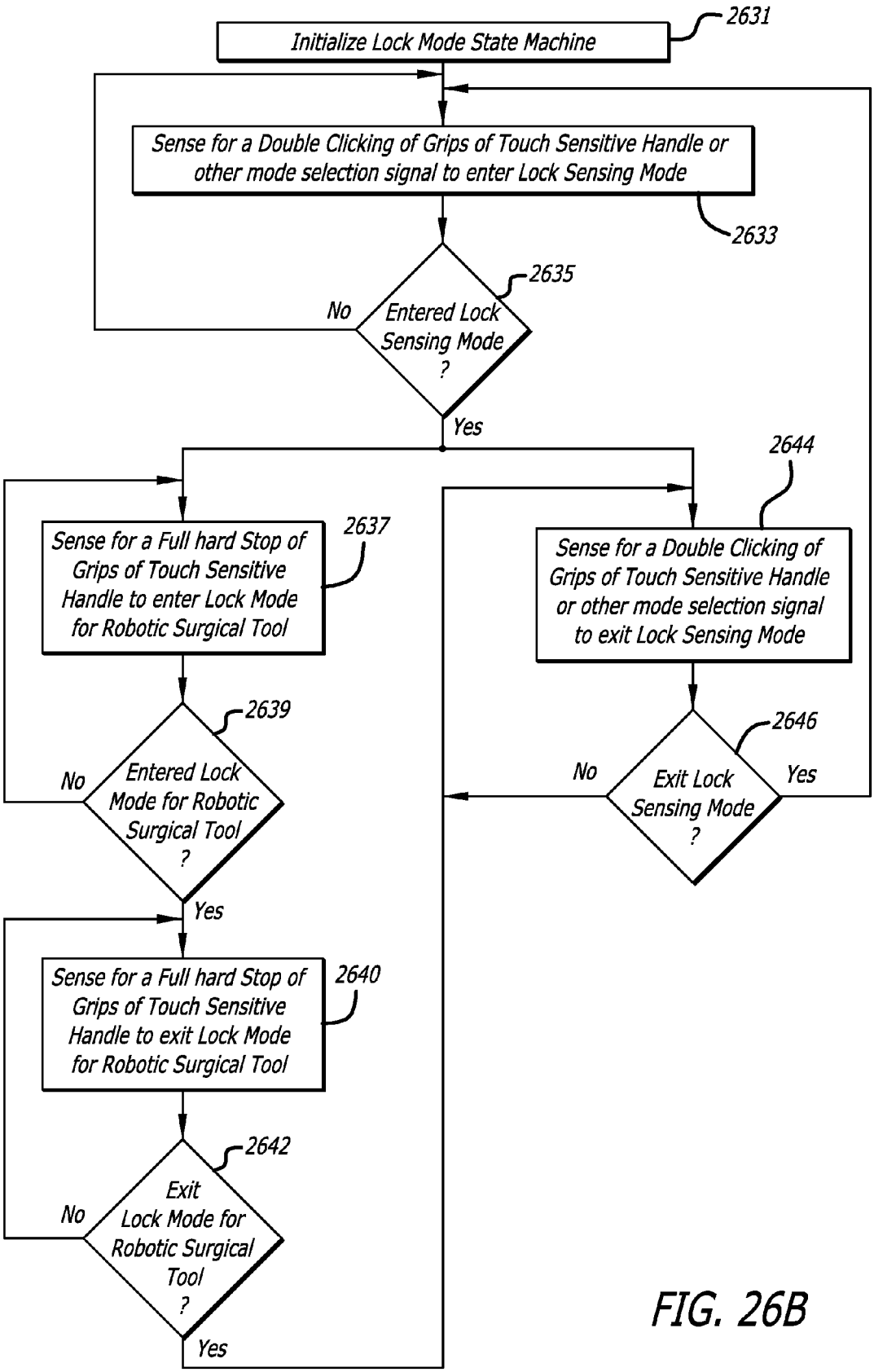
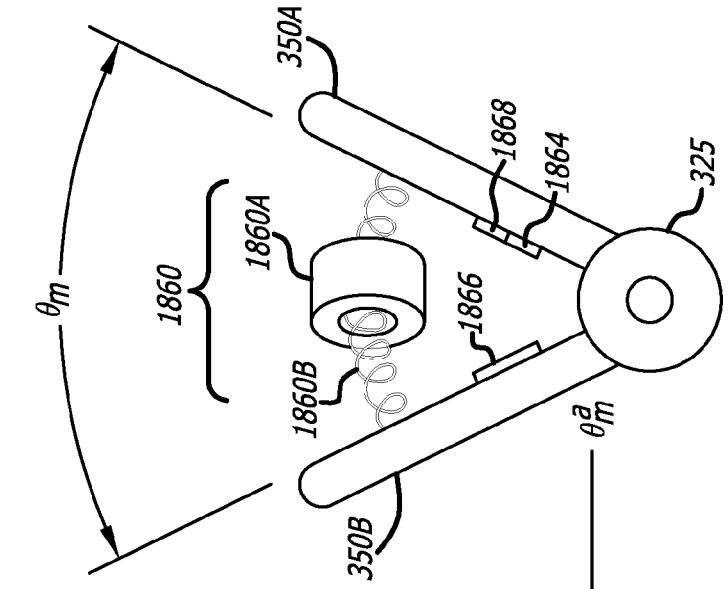

Initialize Lock Mode State Machine
2631
Sense for a Double Clicking of Grips of Touch Sensitive Handle or other mode selection signal to enter Lock Sensing Mode
2633
Entered Lock Sensing Mode ?
2635
No
Yes
Sense for a Full hard Stop of Grips of Touch Sensitive Handle to enter Lock Mode for Robotic Surgical Tool
2637
Entered Lock Mode for Robotic Surgical Tool ?
2639
No
Yes
Sense for a Full hard Stop of Grips of Touch Sensitive Handle to exit Lock Mode for Robotic Surgical Tool
2640
Exit Lock Mode for Robotic Surgical Tool ?
2642
No
Yes
Sense for a Double Clicking of Grips of Touch Sensitive Handle or other mode selection signal to exit Lock Sensing Mode
2644
Exit Lock Sensing Mode ?
2646
No
Yes

FIG. 26B


350A
1868
1864
325
1860A
1860
1866
1860B
350B
θ_m
θ_m^a

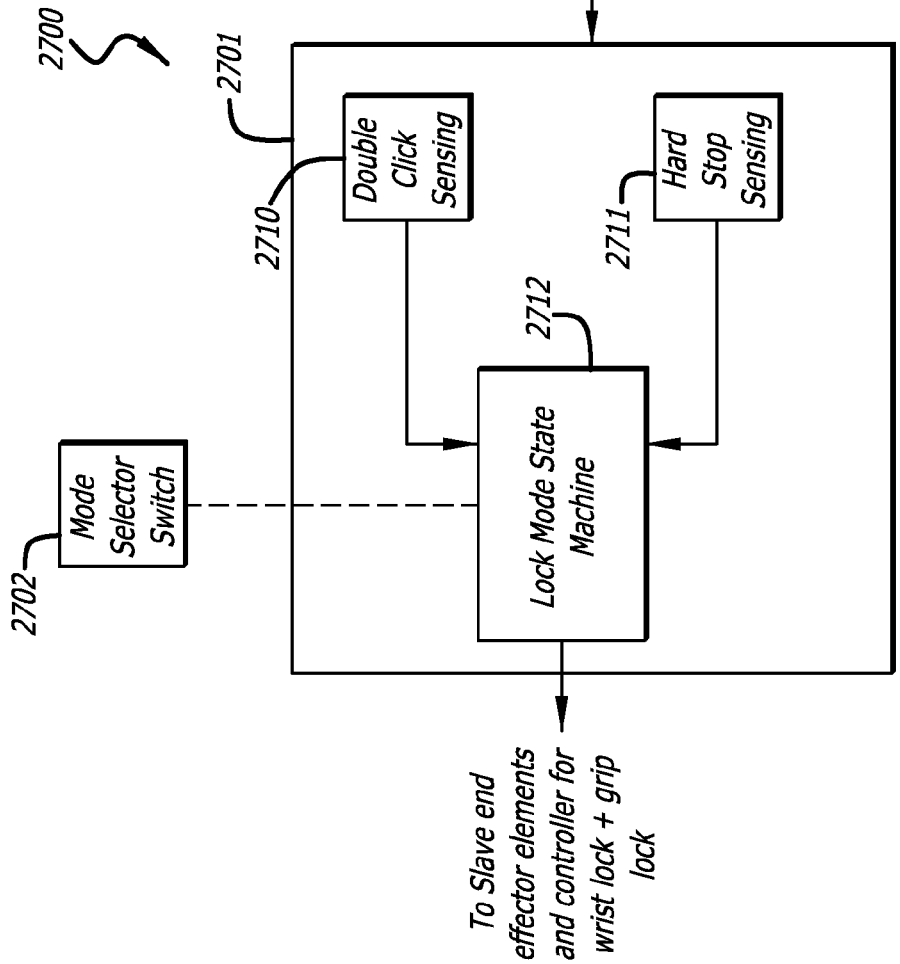

2700
2701
Double Click Sensing
2710
Hard Stop Sensing
2711
2712
Lock Mode State Machine
Mode Selector Switch
2702
To Slave end effector elements and controller for wrist lock + grip lock

FIG. 27

USER INTERFACE METHODS FOR ALTERNATE TOOL MODES FOR ROBOTIC SURGICAL TOOLS

CROSS-REFERENCE TO RELATED APPLICATIONS

This patent application claims the benefit of U.S. Provisional Patent Application No. 60/976,460 filed on Sep. 30, 2007 by inventors Nitish Swamp, et al., entitled USER INTERFACE WITH ALTERNATE TOOL MODE FOR ROBOTIC SURGICAL TOOLS.

FIELD

The embodiments of the invention are generally related to robotic surgical instruments or tools and robotic surgical systems.

BACKGROUND

Minimally invasive surgery typically limits the size of incisions into a human body so that the recovery from surgical procedures may be quick and the odds of infection reduced. However, only a few tools may be concurrently used by the same surgeon during minimally invasive surgery. Sometimes a tool change may occur to place the proper tool within the surgical site. A tool change may extend out the time of a minimally invasive surgical procedure.

Moreover, minimally invasive surgery may be burdensome on a surgeon, particularly when manually operating surgical controls for long periods of time.

BRIEF SUMMARY

The embodiments of the invention are summarized by the claims that follow below.

BRIEF DESCRIPTIONS OF THE DRAWINGS

FIG. **1** is a block diagram of a robotic surgery system to perform minimally invasive robotic surgical procedures using a robotic electro-surgical tool.

FIG. **2**A is a perspective view of a robotic surgical manipulator with a plurality of robotic surgical arms at least one of which includes a robotic electro-surgical tool.

FIG. **2**B is a perspective view of the robotic surgical arm including the robotic electro-surgical tool mounted thereto.

FIG. **2**C illustrates mounting of the robotic electro-surgical tool to an adapter of the robotic surgical arm of FIG. **2**B.

FIG. **2**D illustrates a top view of the adapter of the robotic surgical arm of FIG. **2**C to which the robotic electro-surgical tool may be mounted.

FIG. **3**A is a perspective view of a robotic surgical master control console.

FIG. **3**B is a perspective view of an exemplary gimbaled device pivotally supporting a touch sensitive handle for the robotic surgical master control console of FIG. **3**A to control robotic surgical tools including a robotic electro-surgical tool.

FIG. **3**C is a cross-sectional view schematically illustrating mounting of the touch sensitive handle of FIG. **3**B with sensors to sense gripping and rotation of the handle to control robotic surgical tools, including a robotic electro-surgical tool.

FIGS. **4**A-**4**G illustrate an exemplary robotic electro-surgical instrument or tool with a gripping end effector.

FIGS. **5**A-**5**B are magnified views of a distal end of the robotic electro-surgical tool illustrated in FIG. **4**A with gripping end effectors in a closed position.

FIG. **6**A illustrates a first grip with a recessed electrode.

FIG. **6**B illustrates an opposing second grip with a raised electrode.

FIGS. **7**A and **7**B are exploded view showing the electrode, sleeve, and jaw blade of the end effectors illustrated in FIGS. **5**A-**5**B.

FIG. **8** is a schematic view of the cables and pulleys in the cable drive system of the robotic surgical tool and a robotic surgical arm.

FIG. **9** shows a schematic side view of the cable drive system of FIG. **8** in the robotic surgical tool and the robotic surgical arm with an interface there between.

FIG. **10** shows a three-dimensional schematic view of the cable drive system to the end effectors and wrist mechanism at the end of the robotic surgical tool.

FIG. **11** is a simplified schematic diagram illustrating the force transmission provided by a pair of jaws of the end effectors.

FIG. **12**A is a top view of the surgical instrument shown in FIG. **4** with a housing cover having been removed to show working elements inside a mountable housing.

FIG. **12**B is a side view of a driven element extending through the base of the mountable housing illustrated in FIG. **12**A.

FIGS. **13**A-**13**C illustrate a variety of input disk positions to drive the end effectors.

FIGS. **14**A-**14**C illustrate exemplary actual positions of the end effectors respectively corresponding to the input disk positions of FIGS. **13**A-**13**C.

FIG. **14**D illustrates a desired position of the end effectors that is not reached.

FIGS. **15**A-**15**C illustrate exemplary positions of the master grips respectively corresponding to the input disk positions of FIGS. **13**A-**13**C, the exemplary actual positions of the end effectors of FIGS. **14**A-**14**C, and the desired position of the end effectors of FIG. **14**D.

FIG. **16**A schematically illustrates a high level control architecture model of a master/slave surgical robotic system.

FIG. **16**B shows a block diagram representing control steps followed by the control system of the minimally invasive surgical apparatus in effecting control between master positional and orientational movement and slave end effector positional and orientational movement.

FIG. **17** is a functional block diagram schematically illustrating an enhanced grip force master/slave arrangement in which a mechanical biasing mechanism provides tactile feedback to the system operator.

FIGS. **18**A-**18**B schematically illustrate simplified master/slave control systems to provide a maximum joint torque limit at the joint of the end effectors.

FIG. **19** illustrates a functional block diagram of the torque saturation limiter illustrated in FIGS. **18**A-**18**B.

FIG. **20** graphically illustrates a function for enhancing an error signal by modifying the gain so that the master grip members can apply the maximum joint torque up to the maximum joint torque limits at the joint of the end effectors.

FIGS. **21**A-**21**B schematically illustrate the use of the master grip members to apply the maximum joint torque limit to the joint at the end effectors.

FIG. **22**A graphically illustrates end effector forces.

FIG. **22**B graphically illustrates master grip forces corresponding to the end effector forces illustrated in FIG. **22**A.

FIG. **23** is a flow chart that illustrates an exemplary method of system setup with torque limited drivers for robotic surgical tools.

FIG. **24** is a flow chart that illustrates an exemplary method of operation of robotic surgical tools with torque limited drivers.

FIG. **25**A is a state diagram for one implementation of a state machine.

FIG. **25**B is a state diagram for another implementation of a state machine.

FIG. **25**C is a state diagram for another implementation of a state machine.

FIG. **25**D is a state diagram for an implementation of a state machine with an alternate user input and sensing thereof.

FIG. **25**E is a state diagram for another implementation of a state machine with an alternate user input and sensing thereof.

FIG. **26**A is a flow chart of a method of using a double click user interface.

FIG. **26**B is a flow chart of a method of operation of a double click user interface.

FIG. **27** is a functional block diagram of a user interface system receiving master grip angles from the master grips of a touch sensitive handle.

Note that these figures are for illustration purposes and do not necessarily reflect the actual shape, size, or dimensions of objects being illustrated.

DETAILED DESCRIPTION

In the following detailed description of the embodiments of the invention, numerous specific details are set forth in order to provide a thorough understanding of the embodiments of the invention. However, the embodiments of the invention may be practiced without these specific details. In other instances, well known methods, procedures, components, and circuits have not been described in detail so as not to unnecessarily obscure aspects of the embodiments of the invention.

Introduction

The embodiments of the invention include methods, apparatus, and systems to provide a locking mode for robotic surgical tools.

In one embodiment of the invention, a user interface system for a robotic surgical system is provided including a first alternate sensing process, a second alternate sensing process and a state machine. The first alternate sensing process is provided to detect a first alternate user input of a control input mechanism to enter an alternate sensing mode for the robotic surgical system. The second alternate sensing process is provided to detect a second alternate user input of a control input mechanism to enter an alternate tool mode. The state machine is provided in operational communication with the first alternate sensing process and the second alternate sensing process. The state machine controls a robotic surgical tool in an alternate manner in response to the state machine being in an alternate tool mode.

In another embodiment of the invention a method for a robotic surgical system is provided including the method of sensing for a first alternate user input signal to enter an alternate tool mode; the method of alternatively controlling a robotic surgical tool in response to the alternative tool mode; and in the alternate tool mode, the method of sensing for the first alternate user input signal to exit the alternate tool mode.

In still another embodiment of the invention, a user interface system for a robotic surgical instrument having a number of degrees of freedom of movement is disclosed, including a double click sensing process to detect two closure cycles of a control input mechanism within a predetermined period of time; a hard stop sensing process to detect a predetermined percentage of a hard stop in the movement of the control input mechanism, and a state machine operationally in communication with the double click sensing process and the hard stop sensing process. The state machine switchably reduces the number of degrees of freedom of movement in the robotic surgical instrument in response to two closure cycles of the control input mechanism within the predetermined period of time and movement of the control input mechanism exceeding the predetermined percentage of the hard stop.

In still another embodiment of the invention, a method for a robotic surgical instrument is provided including entering a lock sensing mode for a robotic surgical instrument; in the lock sensing mode, switchably reducing degrees of freedom of movement in the robotic surgical instrument and switchably clamping one or more end effectors of the robotic surgical in response to the degrees of freedom of movement in the robotic surgical instrument being reduced.

In yet another embodiment of the invention, a method for a robotic surgical system is disclosed including sensing for a first mode selection signal to enter a lock sensing mode; sensing for a first hard stop in a control input mechanism to enter a lock mode for a robotic surgical tool; sensing for a second hard stop in the control input mechanism to exit the lock mode for the robotic surgical tool; and sensing for a second mode selection signal to exit the lock sensing mode.

Robotic Surgical Systems

Robotic surgery generally involves the use of a robot manipulator that has multiple robotic manipulator arms. One or more of the robotic manipulator arms often support a surgical tool which may be articulated (such as jaws, scissors, graspers, needle holders, micro dissectors, staple appliers, tackers, suction/irrigation tools, clip appliers, or the like) or non-articulated (such as cutting blades, cautery probes, irrigators, catheters, suction orifices, or the like). One or more of the robotic manipulator arms are often used to support a surgical image capture device such as an endoscope (which may be any of a variety of structures such as a laparoscope, an arthroscope, a hysteroscope, or the like), or, optionally, some other imaging modality (such as ultrasound, fluoroscopy, magnetic resonance imaging, or the like). Typically, the arms will support at least two surgical tools corresponding to the two hands of a surgeon and one image capture device.

Robotic surgery may be used to perform a wide variety of surgical procedures, including but not limited to open surgery, neurosurgical procedures (such as stereotaxy), endoscopic procedures (such as laparoscopy, arthroscopy, thoracoscopy), and the like.

Referring now to FIG. **1**, a block diagram of a robotic surgery system **100** is illustrated to perform minimally invasive robotic surgical procedures using robotic electro-surgical tools **101**A and **101**C. Each of the robotic electro-surgical tools **101**A and **101**C are robotic endoscopic surgical instrument that are manipulated by a slaved robotic manipulator and remotely controlled by control signals received from a master control console. In contrast, manual endoscopic surgical instruments are directly controlled by hand. Robotic electro-surgical tool **101**A is a bipolar electro-surgical tool. Robotic electro-surgical tool **101**C is a mono-polar electro-surgical tool.

A user or operator O (generally a surgeon) performs a minimally invasive surgical procedure on patient P by manipulating input devices at a master control console **150**. A computer **151** of the console **150** directs movement of robotically controlled endoscopic surgical instruments (generally numbered **101**), effecting movement of the instruments using a robotic surgical manipulator **152**. The robotic surgical manipulator **152** may also be referred to as robotic patient-side cart system or simply as a cart. The robotic surgical manipulator **152** has one or more robotic arms **153**. Typically, the robotic surgical manipulator **152** includes at least three robotic manipulator arms **153** supported by linkages, with a central arm supporting an endoscopic camera and the robotic surgical arms **153** to left and right of center supporting tissue manipulation tools and the robotic surgical tool **101**A.

An assistant A may assist in pre-positioning of the robotic surgical manipulator **152** relative to patient P as well as swapping tools or instruments **101** for alternative tool structures, and the like, while viewing the internal surgical site via an assistant's display **154**. The image of the internal surgical site shown to A by the assistant's display **154** and operator O by surgeon's console **150** is provided by one of the surgical instruments **101** supported by the robotic surgical manipulator **152**.

Generally, the robotic arms **153** of robotic surgical manipulator **152** include a positioning portion and a driven portion. The positioning portion of the robotic surgical manipulator **152** remains in a fixed configuration during surgery while manipulating tissue. The driven portion of the robotic surgical manipulator **152** is actively articulated under the direction of the operator O generating control signals at the surgeon's console **150** during surgery. The actively driven portion of the arms **153** is herein referred to as an actuating portion **158**. The positioning portion of the robotic arms **153** that are in a fixed configuration during surgery may be referred to as positioning linkage and/or "set-up joint"**156**,**156'**.

To support electro-surgical robotic tools **101**A, **101**B, the robotic surgical system **100** may further include one or more electrosurgical generators **102**A-**102**B. The one or more electrosurgical generators **102**A-**102**B are controlled by the master console **150** over the control cables **109**A-**109**B by a surgeon operating the master console.

The electrosurgical generator **102**A is a bipolar generator. A pair of wires **106**A-**106**B couple between the bipolar electrosurgical generator **102**A and a bipolar electrosurgical robotic tool **101**A. The pair of wires pair of wires **106**A-**106**B may transfer the energy of the bipolar electrosurgical generator **102**A to a respective pair of end effectors of the bipolar electrosurgical robotic tool **101**A to cauterize or seal tissue.

The electrosurgical generator **102**B is a monopolar generator. A wire **107** couples between the monopolar electrosurgical generator **102**B and a monopolar electrosurgical robotic tool **101**B. A ground wire **108** couples between the monopolar electrosurgical generator **102**B and patient P. The wire **107** may transfer the energy of the monopolar electrosurgical generator **102**B to an end effector of the monopolar electrosurgical robotic tool **101**B to cauterize or seal tissue.

Referring now to FIG. **2**A, a perspective view of the robotic surgical manipulator **152** is illustrated. The robotic surgical manipulator **152** has one or more robotic surgical arms **153**. The robotic arm **153**C includes an electro-surgical robotic tool **101**A coupled thereto. The robotic surgical manipulator **152** further includes a base **202** from which the robotic surgical instruments **101** may be supported. More specifically, the robotic surgical instruments **101** are each supported by the positioning linkage **156** and the actuating portion **158** of the arms **153**. It should be noted that these linkage structures are here illustrated with protective covers **206**,**208** extending over much of the robotic arms. It should be understood that these protective covers **206**,**208** are optional, and may be limited in size or entirely eliminated in some embodiments to minimize the inertia that is manipulated by the servomechanism, and to limit the overall weight of robotic surgical manipulator **152**.

Each of the robotic surgical tools **101**A-**101**C, releasably couple to a moveable carriage **237** near an end of each robotic surgical arm. Each moveable carriage **237**, with the robotic surgical tool mounted thereto, can be driven to translate along a linear guide formation **260** in the actuating portion **158** of the robotic surgical arms **153** in the direction of arrow **257**.

The robotic surgical manipulator **152** generally has dimensions suitable for transporting between operating rooms. It typically can fit through standard operating room doors and onto standard hospital elevators. The robotic surgical manipulator **152** may have a weight and a wheel (or other transportation) system that allows the cart to be positioned adjacent an operating table by a single attendant. The robotic surgical manipulator **152** may be sufficient stable during transport to avoid tipping, and to easily withstand overturning moments that may be imposed at the ends of the robotic arms during use.

Referring now to FIG. **2**B, a perspective view of the robotic surgical arm **153**C is illustrated including the electro-surgical robotic tool **101**A mounted thereto. Each of the robotic manipulating arms **153** preferably includes a linkage **212** that constrains the movement of the surgical tool **101** mounted thereto. More specifically, linkage **212** includes rigid links coupled together by rotational joints in a parallelogram arrangement so that the robotic surgical tool **101**A rotates around a point **215** in space. At the point **215**, the robotic arm can pivot the robotic surgical tool **101**A about a pitch axis **215**A and a yaw axis **215**B. The pitch and yaw axes intersect at the point **215**, which is aligned along a shaft **216** of robotic surgical tool **101**A. The shaft is a rotatable hollow tube with a number of cables of a cable drive system therein.

The robotic arm provides further degrees of freedom of movement to the robotic surgical tool **101**A. Along an insertion axis **215**C, parallel to the central axis of the shaft **216** of the robotic surgical tool **101**A, the robotic surgical tool **101**A may slide into and out from a surgical site as indicated by arrow **257**. The robotic surgical tool **101**A can also rotate about the insertion axis **215**C. As the robotic surgical tool **101**A slides along or rotates about the insertion axis **215**C, the center point **215** is relatively fixed with respect to the base **218**. That is, the entire robotic arm is generally moved in order to maintain or re-position back to the center point **215**.

The linkage **212** of the robotic arm **153** is driven by a series of motors **217** therein in response to commands from a processor or computer. The motors **217** in the robotic arm are also used to rotate and/or pivot the robotic surgical tool **101**A at the point **215** around the axes **215**A-**215**C. If a robotic surgical tool **101** further has end effectors to be articulated or actuated, still other motors **217** in the robotic arm may be used to do so. Additionally, the motion provided by the motors **217** may be mechanically transferred to a different location such as by using pulleys, cables, gears, links, cams, cam followers, and the like or other known means of transfer, such as pneumatics, hydraulics, or electronics.

For endoscopic surgical procedures, the actuating portion **158** of the robotic arm **153** is often fitted with a hollow cannula **219**. The shaft or tube of the robotic surgical tool **101** may be inserted into the hollow cannula **219**. The cannula **219**, which may be releasably coupled to the robotic arm **153**, supports the shaft or tube of the robotic surgical tool **101**,

preferably allowing the tool to rotate around the axis **215**C and move axially through the central bore of the cannula along the axis **215**C.

The robotic surgical tools **101** are generally sterile structures, often being sterilizable and/or being provided in hermetically sealed packages for use. As the robotic surgical tools **101** will be removed and replaced repeatedly during many procedures, a tool holder could potentially be exposed to contamination if the interface directly engages the tool holder. To avoid contamination to a tool holder and possible cross contamination between patients, an adaptor for coupling to robotic surgical tools **101** is provided in a robotic arm of the robotic surgical manipulator.

Referring now to FIGS. **2**C, **2**D, and **4**B, the mounting of the robotic surgical tool **101**A to an adapter **228** of the robotic surgical arm is now briefly described.

The robotic surgical arm **153** may include an adapter **228** to which the electro-surgical robotic tool **101**A or other surgical tool **101** may be mounted. FIG. **2**D illustrates a front side of an exemplary adapter **228**. The front side of the adaptor **128** is generally referred to as a tool side **230** and the opposite side is generally referred to as a holder side (not shown).

FIG. **4**B illustrates a back side of an exemplary electro-surgical robotic tool **400** as the surgical robotic tool **101**A. The robotic surgical tool **400** includes an exemplary mountable housing **401** including an interface base **412** that can be coupled to the adapter **228**. The interface base **412** and the adapter **228** may be electrically and mechanically coupled together to actuate the robotic surgical tool **400**. Rotatably coupled to the interface base **412** are one or more rotatable receiving members **418**, also referred to as input disks. Each of the one or more rotatable receiving members **418** includes a pair of pins **422**A and **422**B generally referred to as pins **422**. Pin **422**A is located closer to the center of each rotatable receive member **418** than pin **422**B. The one or more rotatable receiving members **418** can mechanically couple respectively to one or more rotatable drivers **234** of the adapter **228**. The robotic surgical tool **101**A may further include release levers **416** to release it from the adapter **228**.

The interface base **412** may further include one or more electrical contacts or pins **424** to electrically couple to electrical connector **242** of the adapter **228**. The interface base **412** may further include a printed circuit board **425** and one or more integrated circuits **426** coupled thereto and to the one or more pins **424**. The one or more integrated circuits **426** may be used to identify the type of robotic surgical tool coupled to the robotic arm, so that it may be properly controlled by the master control console **150**.

The adapter **228** includes one or more rotatable drivers **234** rotatably coupled to a floating plate **236**. The rotatable drivers **234** are resiliently mounted to the floating plate **236** by resilient radial members which extend into a circumferential indentation about the rotatable drivers. The rotatable drivers **234** can move axially relative to floating plate **236** by deflection of these resilient structures.

The floating plate **236** has a limited range of movement relative to the surrounding adaptor structure normal to the major surfaces of the adaptor. Axial movement of the floating plate helps decouple the rotatable drivers **234** from a robotic surgical tool **101** when its release levers **416** are actuated.

The one or more rotatable drivers **234** of the adapter **228** may mechanically couple to a part of the surgical tools **101**. Each of the rotatable drivers **234** may include one or more openings **240** to receive protrusions or pins **422** of rotatable receiving members **418** of the robotic surgical tools **101**. The openings **240** in the rotatable drivers **234** are configured to accurately align with the rotatable receiving elements **418** of the surgical tools **101**.

The inner pins **422**A and the outer pins **422**B of the rotatable receiving elements **418** respectively align with the opening **240**A and the opening **240**B in each rotatable driver. The pins **422**A and openings **240**A are at differing distances from the axis of rotation than the pins **422**B and openings **240**B so as to ensure that rotatable drivers **234** and the rotatable receiving elements **418** are not aligned 180 degrees out of phase from their intended position. Additionally, each of the openings **240** in the rotatable drivers may be slightly radially elongated so as to fittingly receive the pins in the circumferential orientation. This allows the pins **422** to slide radially within the openings **240** and accommodate some axial misalignment between the tool and the adapter **228**, while minimizing any angular misalignment and backlash between the rotatable drivers **234** and the rotatable receiving elements **418**. Additionally, the interaction between pins **422** and openings **240** helps restrain the robotic surgical tool **101** in the engaged position with the adapter **228** until the release levers **416** along the sides of the housing **401** push on the floating plate **236** axially from the interface so as to release the tool **101**.

When disposed in a first axial position (away from the tool side **230**) the rotatable drivers are free to rotate without angular limitation. The one or more rotatable drivers **234** may rotate clockwise or counter-clockwise to further actuate the systems and tools of the robotic surgical instruments **101**. However, as the rotatable drivers move axially toward the tool side **230**, tabs (extending radially from the rotatable drivers) may laterally engage detents on the floating plates so as to limit the angular rotation of the rotatable drivers about their axes. This limited rotation can be used to help engage the rotatable drivers the rotating members of the tool as the pins **422** may push the rotatable bodies into the limited rotation position until the pins are aligned with (and slide into) the openings **140** in the rotatable drivers.

While rotatable drivers **234** are described here, other types of drivers or actuators may be provided in the adapter **228** to actuate systems or tools of the robotic surgical instruments **101**. The adapter **228** further includes an electrical connector **242** to electrically couple to surgical instruments **101**.

The mounting of robotic surgical tool **101**A to the adapter **228** generally includes inserting the tip or distal end of the shaft or hollow tube of the robotic surgical tool through the cannula **219** and sliding the interface base **412** into engagement with the adapter **228**, as illustrated in FIG. **2**C. A lip **232** on the tool side **130** of the adaptor **128** slidably receives the laterally extending portions of the interface base **412** of the robotic surgical tool. A catch **244** of adapter **228** may latch onto the back end of the interface base **412** to hold the tool **101**A in position. The protrusions or pins **422** extending from the one or more rotatable members **418** of the robotic surgical tool couple into the holes **240** in the rotatable drivers **234** of the adapter **228**.

The range of motion of the rotatable receiving elements **418** in the robotic surgical tool may be limited. To complete the mechanical coupling between the rotatable drivers of the adapter and the rotatable receiving elements **418**, the operator O at the surgical master control console **150** may turn the rotatable drivers in one direction from center, turn the rotatable drivers in a second direction opposite the first, and then return the rotatable drivers to center. Further, to ensure that the pins **422** enter openings **240** of adapter **228**, the adapter **228** and tool **101**A mounted thereto may be moved along the axis **215**C. The adapter **228** and tool **101**A mounted thereto

may be moved to an initial position so that the tip or distal end of the shaft or hollow tube is disposed within the cannula **219**.

To dismount and remove the robotic surgical tool **101**A, the release levers **416** may be squeezed pushing out on the mountable housing **401** to release the pins **422** from the holes **240** and the catch **244** from the back end of the interface base. The mountable housing **401** is then pulled up to slide the interface base **412** up and out from the adapter **228**. The mountable housing **401** is continually pulled up to remove the tip or distal end of the shaft or hollow tube out from the cannula **219**. After the robotic surgical tool **101**A is dismounted, another robotic surgical tool may be mounted in its place, including a new or freshly sterilized electro-surgical robotic tool **400**.

As previously discussed, the robotic surgical tool **101**A may include one or more integrated circuits **426** to identify the type of robotic surgical tool coupled to the robotic arm, such that it may be properly controlled by the master control console **150**. However, the robotic surgical system may determine whether or not the robotic surgical tool is compatible or not, prior to its use.

The system verifies that the tool is of the type which may be used with the robotic surgical system **100**. The one or more integrated circuits **426** may signal to the computer **151** in the master control console **150** data regarding compatibility and tool-type to determine compatibility as well as control information. One of the integrated circuits **426** may include a non-volatile memory to store and read out data regarding system compatibility, the tool-type and the control information. In an exemplary embodiment, the data read from the memory includes a character string indicating tool compatibility with the robotic surgical system **100**. Additionally, the data from the tool memory will often include a tool-type to signal to the master control console how it is to be controlled. In some cases, the data will also include tool calibration information. The data may be provided in response to a request signal from the computer **151**.

Tool-type data will generally indicate what kind of tool has been attached in a tool change operation. For example, the tool-type data might indicate that an electro-surgical robotic instrument **101**A has been mounted to the robotic arm. The tool-type data may include information on wrist axis geometries, tool strengths, grip force, the range of motion of each joint, singularities in the joint motion space, the maximum force to be applied via the rotatable receiving elements **418**, the tool transmission system characteristics including information regarding the coupling of rotatable receiving elements **418** to actuation or articulation of a system within the robotic surgical instrument.

Instead of storing all of the tool-type date in the one or more integrated circuits **426**, most of the tool-type data may optionally be stored in memory or a hard drive of the computer **151** in the robotic surgical system **100**. An identifier may be stored in the one or more integrated circuits **426** to signal the computer **151** to read the relevant portions of data in a look up table store in the memory or the hard drive of the computer. The tool-type data in the look-up table may be loaded into a memory of computer **151** by the manufacturer of the robotic surgical system **100**. The look-up table may be stored in a flash memory, EEPROM, or other type of non-volatile memory. As a new tool-type is provided, the manufacturer can revise the look-up table to accommodate the new tool-specific information. It should be recognized that the use of tools which are not compatible with the robotic surgery system, for example, which do not have the appropriate tool-type data in an information table, could result in inadequate robotic control over robotic surgical tool by the computer **151** and the operator O.

In addition to the tool-type data, tool specific information may be stored in the integrated circuit **426**, such as for reconfiguring the programming of computer **151** to control the tool. There may be calibration information, such an offset, to correct a misalignment in the robotic surgical tool. The calibration information may be factored into the overall control of the robotic surgical tool. The storing of such calibration information can be used to overcome minor mechanical inconsistencies between tools of a single type. For example, the tool-type data including the tool-specific data may be used to generate appropriate coordinate transformations and servo drive signals to manipulate the robotic arm and rotate the rotatable drivers **234**. In this case, the integrated circuit **426** includes the information to set up the control system to drive the end effectors in the tool to have a maximum joint torque setting so that the jaws of a robotic gripping tool or a robotic electrosurgical tool can clamp to tissue with a maximum force.

Additionally, some robotic surgical tools have a limited life span. Tool life and cumulative tool use information may also be stored on the tool memory and used by the computer to determine if the tool is still safe for use. Total tool life may be measured by clock time, by procedure, by the number of times the tool has been loaded onto a holder, and in other ways specific to the type of tool. Tool life data is preferably stored in the memory of the tool using an irreversible writing process.

Referring now to FIG. **3**A, a perspective view of a robotic surgical master control console **150** is illustrated. The master control console **150** of the robotic surgical system **100** includes the computer **151**, a binocular viewer **312**, an arm support **314**, a microphone **315**, a pair of control input wrists and control input arms in a workspace **316**, a speech recognizer **317**, foot pedals **318** (including foot pedals **318**A-**318**B), and a viewing sensor **320**.

The computer **151** may include one or microprocessors **302** to execute instructions and a storage device **304** to store software with executable instructions that may be used to generate control signals to control the robotic surgical system **100**. The master control console **150** generates the control signals to control the electro-surgical robotic instruments in a surgical site.

The viewer **312** has at least one display where images of a surgical site may be viewed to perform minimally invasive surgery.

The arm support **314** can be used to rest the elbows or forearms of the operator O (typically a surgeon) while gripping touch sensitive handles **325** (see FIGS. **3**B-**3**C), one in each hand, of the pair of control input wrists **352** in the workspace **316** to generate control signals. The touch sensitive handles **325** are positioned in the workspace **316** disposed beyond the arm support **314** and below the viewer **312**.

When using the master control console, the operator O typically sits in a chair, moves his or her head into alignment with the binocular viewer **312**, and grips the touch sensitive handles **325** of the control input wrists **352**, one in each hand, while resting their forearms against the arm support **314**. This allows the touch sensitive handles to be moved easily in the control space **316** in both position and orientation to generate control signals.

Additionally, the operator O can use his feet to control the foot-pedals to change the configuration of the surgical system and generate additional control signals to control robotic surgical instruments.

To ensure that the operator is viewing the surgical site when controlling the robotic surgical tools **101**, the master control console **150** may include the viewing sensor **320** disposed adjacent the binocular display **312**. When the system operator aligns his or her eyes with the binocular eye pieces of the display **312** to view a stereoscopic image of the surgical worksite, the operator's head sets off the viewing sensor **320** to enable the control of the robotic surgical tools **101**. When the operator's head is removed the area of the display **312**, the viewing sensor **320** can disable or stop generating new control signals in response to movements of the touch sensitive handles in order to hold the state of the robotic surgical tools.

The computer **151** with its microprocessors **302** interprets movements and actuation of the touch sensitive handles **325** (and other inputs from the operator O or other personnel) to generate control signals to control the robotic surgical instruments **101** in the surgical worksite. In one embodiment of the invention, the computer **151** and the viewer **312** map the surgical worksite into the controller workspace **316** so it feels and appears to the operator that the touch sensitive handles **325** are working over surgical worksite.

Referring now to FIG. **3**B, a perspective view of a control input wrist **352** with a touch sensitive handle **325** is illustrated. The control input wrist **352** is a gimbaled device that pivotally supports the touch sensitive handle **325** of the master control console **150** to generate control signals that are used to control the robotic surgical manipulator **152** and the robotic surgical tools **101**, including electro-surgical robotic tool **101**A,**101**C. A pair of control input wrists **352** are supported by a pair of control input arms in the workspace **316** of the master control console **150**.

The control input wrist **352** includes first, second, and third gimbal members **362**, **364**, and **366**. The third gimbal member is rotationally mounted to a control input arm (not shown).

The touch sensitive handle **325** includes a tubular support structure **351**, a first grip **350**A, and a second grip **350**B. The first grip and the second grip are supported at one end by the structure **351**. The touch sensitive handle **325** can be rotated about axis G illustrated in FIGS. **3**B-**3**C. The grips **350**A, **350**B can be squeezed or pinched together about the tubular structure **351**. The "pinching" or grasping degree of freedom in the grips is indicated by arrows Ha,Hb in FIG. **3**B and arrows H in FIG. **3**C.

The touch sensitive handle **325** is rotatably supported by the first gimbal member **362** by means of a rotational joint **356***g*. The first gimbal member **362** is in turn, rotatably supported by the second gimbal member **364** by means of the rotational joint **356***f*. Similarly, the second gimbal member **364** is rotatably supported by the third gimbal member **366** using a rotational joint **356***d*. In this manner, the control wrist allows the touch sensitive handle **325** to be moved and oriented in the workspace **316** using three degrees of freedom.

The movements in the gimbals of the control wrist **352** to reorient the touch sensitive handle in space can be translated into control signals to control the robotic surgical manipulator **152** and the robotic surgical tools **101**.

The movements in the grips **350**A,**350**B of the touch sensitive handle **325** can also be translated into control signals to control the robotic surgical manipulator **152** and the robotic surgical tools **101**. In particular, the squeezing motion of the master grips **350**A,**350**B over their freedom of movement indicated by arrows Ha,Hb or H, may be used to control the end effectors of the robotic surgical tools.

To sense the movements in the touch sensitive handle **325** and generate controls signals, sensors can be mounted in the handle **325** as well as the gimbal member **362** of the control input wrist **352**. Exemplary sensors may be a Hall effect transducer, a potentiometer, an encoder, or the like.

Referring now to FIG. **3**C, a cross-sectional view of the touch sensitive handle **325** and gimbal member **362** of the control input wrist **352** is illustrated. FIG. **3**C provides an example as to how the touch sensitive handle **325** can be mounted to the control input wrist **352** to sense the gripping and rotation of the handle to control robotic surgical tools **101**.

As illustrated in FIG. **3**C, the exemplary gimbal member **362** includes beveled gears **368***a*, **368***b* which can couple the rotational motion of the touch sensitive handle **325** to a roll sensor **370**. The roll sensor **370** may use a potentiometer or encoder **370***b* included in a roll motor **370***a* to sense the rotation. Alternatively, a separate roll sensor, such as a potentiometer, may be directly coupled to the shaft **380** to sense the rotation of the touch sensitive handle. In any case, a roll sensor senses the roll motion of the touch sensitive handle **325** and generates control signals in response thereto to control the robotic surgical tools **101**.

To sense a squeezing motion in the grips **350**A,**350**B of the touch sensitive handle **325**, a remote sensing assembly **386** may be included by the gimbal member **362**. The first and second grips **350**A,**350**B are adapted to be squeezed together by a hand of an operator O so as to define a variable grip separation. The grip separation may be determined as a function of a variable grip angle with an axis or as a function of a variable grip separation distance, or the like. Alternative handle actuations, such as movement of a thumbwheel or knob may also be provided in the handle to control the robotic surgical instruments **101**.

In the exemplary embodiment, the remote sensor assembly **386** includes a circuit board **394** on which a first and a second Hall effect sensors, HE**1**, HE**2** are mounted. A magnet **396** is disposed distally beyond the circuit board **394** and the Hall effect sensors. A magnetic mass **398** is axially coupled to the proximally oriented surface **390** of a push rod **84**. Thus, the magnetic mass **398** moves (as shown by Arrow J) with the push rod **384** and varies the magnetic field at the Hall effect sensors in response actuation of the grips **350**A,**350**B.

To translate the squeezing action of the grips **350**A,**350**B to the sensor **386**, the gimbal member **362** includes a push rod **384** within the tubular handle structure **351**. Each of the grips **350**A, **350**B pivot about a respective pivot **334***a*, **334***b* in the tubular handle structure **351**. Urging links **335***a*, **335***b* respectively couple between the grips **350**A,**350**B and a first end of the push rod **384**. The squeezing action of the grips **350**A, **350**B is translated into a linear motion on the push rod **384** by means of urging links **335***a*,**335***b* as shown by arrow A in FIG. **3**C. A second end of the push rod **384** couples to the sensor **386**. As discussed previously, the magnetic mass **398** is axially coupled to the surface **390** of the push rod **384** in order to sense the linear motion in the push rod and the squeezing motion of the grips **350**A,**350**B.

A biasing mechanism such as spring **392** applies a force against the squeezing motion of the grips to return them to full open when the grips are released. The biasing spring **392** may be a linear or non-linear elastic device biasing against the depression of grips **350**A, **350**B, e.g., a single or multiple element assembly including springs or other elastic members. For example, spring **392** may comprise a concentric dual spring assembly whereby one spring provides a "softer" bias response as the grips **350**A, **350**B are initially depressed, and a second spring provides a superimposed "firm" bias response as the grips **350**A, **350**B approach a fully depressed state. Such a non-linear bias may provide a pseudo force-feedback to the operator.

It should be noted that a wide variety of alternative sensing arrangements may be used to translate the mechanical actuation of the touch sensitive handle and control input wrist into control signals. While Hall effect sensors are included in the exemplary embodiment, alternative embodiments may include encoders, potentiometers, or a variety of alternative optical, electrical, magnetic, or other sensing structures.

Electro Surgical Instruments

Exemplary embodiments of robotic electro surgical tools that can be mounted to a robotic arm in a robotic surgical system are now described. However, further details of robotic electro-surgical tools may be described in U.S. patent Nos. with filing dates and named inventor as follows U.S. Pat. No. 6,840,938, Dec. 21, 2001, Morley et al.; and U.S. Pat. No. 6,994,708, Apr. 18, 2002, Scott Manzo; and application Ser. No. 10/726,795, Dec. 2, 2003, Cooper et al.; application Ser. No. 10/611,411, Jun. 30, 2003, Manzo et al.; application Ser. No. 11/238,698, Sep. 28, 2005, Manzo et al.; and application Ser. No. 11/238,794, Sep. 28, 2005, Scott Manzo, all of which are incorporated herein by reference.

Robotic surgical instruments **101** mounted on the robotic surgical arms **153** typically include elongated shafts, with proximal and distal ends. End effectors are generally mounted on wrist-like mechanisms pivotally mounted on the distal ends of the shafts, for enabling the instruments **101** to perform one or more surgical tasks. Generally, the elongate shafts of surgical instruments **101** allow the end effectors to be inserted through entry ports in a patient's body so as to access the internal surgical site. Movement of the end effectors is generally controlled via master controls on the master console **150**.

Electrosurgical instruments and systems, as well as methods of performing minimally invasive robotic surgical procedures with such instruments are now disclosed. The instruments of the embodiments of the invention are capable of treating tissue with heat produced by electrical energy while cutting, shearing, grasping, engaging, or contacting treatment tissue. Electrosurgical instruments may apply a high-frequency alternating current to surrounding tissue, thereby to cause the tissue temperature to rise to the point where the tissue is cut or coagulates. Alternatively, electrosurgical instruments may apply heat to tissue by means of electrically generated heat inside the instrument. The electrosurgical treatment may further reduce bleeding of tissue by cauterizing tissue and coagulating blood, or achieve various other desired effects on the treatment tissue such as sealing tissue together. The electrosurgical treatment is carried out in a safe and effective manner that incorporates a variety of safety features to prevent current leakage to non-target tissue so as to reduce collateral tissue damage, unwanted burning, or the like. The fact that a cauterizing action is provided and the nature thereof should not be understood as limiting to the embodiments of the present invention.

Referring to FIGS. **4**A-**4**E, a robotic electro-surgical tool or instrument **400** is illustrated in greater detail than that of instruments **101**A and **101**C. The robotic electro-surgical tool or instrument **400** includes a mountable housing **401**, an elongated shaft **416** having a proximal end and a distal end; and end effectors **414**A-**414**B (collectively referred to by **414**) coupled near the distal end of the shaft **416**. The mountable housing **401** includes an interface or tool base **412** coupled to the proximal end of the shaft **416**. The mountable housing **401** may further include one or more electrical connectors **474**, **474**A-**474**B, a cover **472**, and one or more release levers **417**. At the distal end of the shaft **416** is a mechanical wrist **402** to move the end effectors **414**.

The interface or tool base **412** can couple to the adapter **228** to which other surgical tools may also couple so that the electrosurgical tool **400** is removably connectable to the robotic surgical system. During surgery, the adapter **228** is coupled to the moveable carriage **237**. Thus, with the electrosurgical tool **400** mounted to the adapter **228**, it can translate with the carriage **237** along the actuating portion of the robotic surgical arm **153**.

When mounted to a robotic surgical arm **153**, end effectors **414** may have a plurality of degrees of freedom of movement relative to arm **153**, in addition to actuation movement of the end effectors. As discussed previously, the electrosurgical tool **400** may be translated along an insertion axis as indicated by arrow **257** in FIG. **2**A. The elongated shaft **416** is rotatably mounted to the base **412** for rotation about an axis **450** extending longitudinally along the shaft **450** as indicated by the rotational arrow A**3**. The wrist **402** may be a single pivot wrist, a multi-pivot wrist, a distal roll joint mechanism, or other joints or wrist-like mechanism to provide additional operational degrees of freedom to the end effector. The wrist **402** may pivot around an axis **451** at a pivot point as indicated by the rotational arrow A**1**. The end effectors **414**A,**414**B may pivot together as a whole about pivot point **432** as indicated by arrow A**2**.

The orientation of the mechanical wrist **402** is controlled through pulleys in the tool base **412** and the wrist **402** with cables of cable loops wrapped around each being routed through the shaft **416**. The robotic system causes the pulleys in the tool base **412** to be rotated in order to control the position of the mechanical wrist **402**, and the end effectors **414**. Thus, the cable of the cable loops may also be referred to as a control cable. That is, the end effectors **414** are actuated from the tool base **412** through a cable loop, pulleys, and a spool similar to how other elements of the wrist **402** are controlled. In this case, two cable loops are used to actuate the end effectors **414**, one cable loop for each.

Further details of mechanical wrists that may be applicable to the mechanical wrist **402** are described in U.S. patent Nos. with filing dates and named inventor as follows U.S. Pat. No. 5,792,135, May 16, 1997, Madhani et al; U.S. Pat. No. 5,979,900, May 16, 1997, Madhani et al; U.S. Pat. No. 5,807,377, May 16, 1997, Madhani et al; U.S. Pat. No. 6,206,903, Oct. 8, 1999, Ramans; U.S. Pat. No. 6,312,435, Oct. 8, 1999, Wallace et al.; U.S. Pat. No. 6,371,952, Jun. 28, 1999, Madhani et al; U.S. Pat. No. 6,394,998, Sep. 17, 1999, Wallace et al.; U.S. Pat. No. 6,676,684, Sep. 4, 2001, Morley et al.; U.S. Pat. No. 6,685,698, Jan. 10, 2003, Morley et al.; U.S. Pat. No. 6,699,235, Mar. 2, 2004, Wallace et al.; U.S. Pat. No. 6,746,443, Jul. 27, 2000, Morley et al.; and U.S. Pat. No. 6,817,974, Jun. 28, 2002, Cooper et al., all of which are incorporated herein by reference.

The end effectors **414** are used in performing a surgical operation such as cutting, shearing, grasping, engaging, or contacting tissue adjacent a surgical site. In one embodiment of the invention, the end effectors **414** includes a pair of gripping jaws for clamping onto tissue. Additionally, a conductor electrically communicates with at least one of the end effectors to deliver electrical energy to tissue clamped by the gripping jaws.

As shown in FIG. **4**B, the tool base **412** may be enclosed by a cover **472** which mounts an electrical connector **474**. A conductor **448** is electrically coupled to the electrical connector **474** at one end and at least one end effector at the opposite end.

Referring now to FIG. **4**C, an insulated conductor **448** passes out from the shaft **416** to the rear of base **412** to the electrical connector **474** for connection to the monopolar electrosurgical generator. The conductor **448** communicates with at least one of the end effectors, to deliver electrical energy to tissue from an electrosurgical generator G, such as the monopolar generator **102**B illustrated in FIG. **1**. The tool base **412** may further support a bipolar generator **102**A by adding an extra wire connection to the connector **474** or by adding an extra electrical connector **474** and routing two wires to each of the two end effectors.

As discussed previously, the end effectors **414** are actuated from the tool base **412** through a cable of a cable loop, pulleys, and an actuating spool. A cable loop CL may be considered to be a single cable routed in a loop around the drive pulley from the spool in the tool base. A cable loop may be formed by joining or splicing different segments of cable together. Each side of the cable loop CL may be referred to as being a cable. In order to prevent slippage, a cable may be fixed to a pulley, shaft, capstan and/or tube at one point by soldering, welding, crimping or other mechanical fixing means.

The tool base **412** includes actuating spools **434**A-**434**C, guide pulleys **435**A-**435**B, and cable loops CL **436**A-**436**C to form driven elements control the mechanical wrist **402** and the end effectors **414**. The details of a driven element are discussed further below with reference to FIG. **12**B. Each of the driven elements includes receiving elements or input disks (not visible in FIG. **4**C) that releasably couple through an adapter to a rotatable driving element that is mounted on the carriage **237** of the robotic arm assembly **153**. The rotatable driving elements of the carriage **237** are generally coupled to actuators (not shown), such as electric motors or the like, to cause selective angular displacement of each in the carriage **237**. Selective actuation of the actuators is transmitted through the rotatable driving element on the carriage **137**, to the input disks of the tool **400** and cause selective angular displacement of the actuating spools **434**A-**434**C. This is described in greater detail below with reference to FIGS. **8**-**12**B. Where more or fewer degrees of freedom are desired, the number of spools may be decreased or increased.

Referring now to FIG. **4**G, to inhibit stretching of the cables C along their lengths and along the shaft **416**, elongate relatively rigid members, e.g., hypotube portions **33**, may be used. The hypotube portions **433** couple to opposed Tungsten cable portions **437**, **438** at each end. Ends of the Tungsten cable portions **437**, **438** are typically crimped into opposing ends of the hypotubes as indicated by crimps **439**. The hypotubes **433** are typically hollow tubes having a circular cross-section. One or more of the cables C may also include a non-conductive portion or an insulator portion **456** coupled between hypotube portions. This may be particularly useful for robotic electro-surgical tools and a live end effector in isolating the current and voltages applied to tissue from other parts of the instrument and system. Regardless of the use of hypotube portions **433** and insulative portions **456**, the cabling, hypotube, and insulative portions may be referred to as cables C of a cable loop CL. Note that the cables C, at least in the region of the wrist, are typically made of metal, such as Tungsten or stainless steel, to provide sufficient strength, bendability and durability.

The cables of the cable loops **436**A-**434**C are routed from the actuating spools over the guide pulleys **435**A-**435**B and through the shaft **416** to drive pulleys in the wrist **402**. The tool base **412** further includes a spool **464** and a drum **462** with a cable loop coupled there-between to control the rotation of the shaft **416** and the wrist **402**.

A first end of the cable of each cable loop is wrapped in one direction around the spool with the second end of the cable wrapped in an opposite direction around the same spool. In this manner, one end of cable is taken up while the other end of the cable is released during the rotation of a spool. Each spool includes a tension mechanism to avoid slack in the cable of each cable loop.

The shaft of each spool extends through the tool base **412** to its underside to couple to an engaging member. The engaging member can releasably couple to a complimentary engaging member that is in turn coupled to an actuator of the surgical system, such as an electric motor, to cause an angular displacement in the spool in response to a control signal from the control console.

An optional flush tube **476** may be mounted to a tool base cover **472** by a flush port **478** and the assembled base **412**. The flush tube preferably extends forward (distally) within the base **412** to communicate with the shaft **416** to permit fluids to be passed through the shaft **416** and/or to pressurize the shaft **416**. For example, introduction of insufflation gas during surgery or the introduction of cleaning or sterilization gases or fluids prior and/or subsequent to surgery may be passed to the shaft **416** via flush tube **476**. U.S. Pat. No. 6,004,509 describes the use of fluids and gases to maintain sterility of a surgical instrument, and is incorporated herein by reference.

Referring now to FIGS. **4**D and **4**E, the base cover **472** mounts an electrical connector **474**, in this case, a banana clip assembly **474***a*, **474***b*, and **474***c*, for the insulated conductor **448** to permit connection to an electrosurgical generator. Note that the connections described above provide an insulated continuous electrical path from the base connector **474** to the end effectors **414**A-**414**B protected from tissue contact except at the jaw portions thereof. Energization of one or both of the end effectors **414**A-**414**B is controllable by the surgeon.

FIG. **4**F illustrates a back side view of a portion of the robotic surgical tool **400**, some elements of which were previously discussed. In particular, the interface base **412** is illustrated with rotatable receiving elements ("input disks") **418** rotatably coupled thereto. The interface base **412** is used to mount the instrument **400** to a robotic arm of a surgical robotic manipulator. The interface base **412** both mechanically and electrically couples the surgical instrument **400** to a robotic arm of the surgical robotic manipulator **152**. The release levers **416** are located at the sides of the mountable housing and may be used to release the robotic surgical instrument **400** from a robotic arm.

The rotatable receiving elements **418** provide a mechanical coupling to the rotatable drivers **234** and drive motors mounted in the robotic surgical arm **153** and the robotic surgical manipulator **152**. Each of the rotatable receiving elements **418** includes a pair of pins **422** extending from a surface thereof. An inner pin **422**A is closer to an axis of rotation of each rotatable receiving elements **418** than an outer pin **422**B, which helps to ensure positive angular alignment of the rotatable receiving elements **418**. In one embodiment of the invention, the rotatable receiving elements **418** are disk shaped and are also referred to herein as "input disks".

The interface base **412** further includes an array of electrical connecting pins **424** and one or more integrated circuits **426** coupled to a printed circuit board **425** within the mountable housing **401**. As the interface base **412** is backward compatible to the adapter **228**, it maybe mechanically actuated by pre-existing driver motors found in the robotic surgical manipulator **152**. While the interface base **412** has been described herein with reference to mechanical and electrical

coupling elements, it should be understood that other modalities maybe used, including infrared coupling, magnetic coupling, inductive coupling, or the like.

Referring momentarily now to FIG. **9**, a schematic view of the electrocautery surgical instrument **400** is illustrated. The electrocautery instrument **400** may be used to generate an electrical current at a surgical site so as to burn or seal, e.g., ruptured blood vessels.

In a monopolar electrosurgical system, the patient is earthed and a voltage is supplied to the electrode coupled to the end effector. An electrically conductive cable **448** extends from a plug **474** on the housing **401** to the electrode at the end effector **812**A,**812**B. This conductive cable, or cautery wire, may include a "service loop" around a joint axis at the wrist. The service loop, a single loose wrap around the joint, permits rotation of the cautery blade about the axis without placing undue stress or stretch on the wire during such rotation. It will be appreciated that, in use, the plug **474** is releasably connected to an appropriate electrical source. The plug **474** is typically a conventional banana-type plug. The housing **401** is typically of a non-conductive plastics material.

It has been found that it is best to insulate the electrode at the end effectors from the rest of the instrument **400** so as to inhibit current leakage from the electrode to other elements in the instrument **400**. It will be appreciated that should the distance between the electrode and the patient be relatively great when a voltage is applied, current may jump from the electrode to other conductive parts of the instrument. In such a case, current can be passed from the instrument **400** to the patient along a path of least resistance, e.g., at the entry port of the shaft coincident with its center of rotation. This may cause unnecessary burning at the entry port. Furthermore, the current may be passed along the instrument **400** to the telesurgical system in general and may be damaging to sensitive electronics, e.g., forming part of the endoscope and viewer arrangement.

Accordingly, the wrist mechanism **402**,**850** wherever possible is made of non conductive material. The wrist member **402**,**850** and the various pulleys are typically made from non-conductive plastic, e.g., polyethermide or ULTEM. Alternatively, a conductive wrist can be sheathed in a non-conductive material.

The conductive cable **448** is typically sheathed in an insulative material such as, e.g., polytetrafluoroethylene or TEFLON. The conductive cable is electrically coupled the electrode at the end effector **812**A,**812**B. The electrode may be removably mountable on the end effector **812**A,**812**B. Accordingly, a conductive seat or sleeve may be used to provide an electrical connection to the electrode when in a mounted condition.

The shaft **416** is typically made entirely from a nonconductive material, or at least sheathed in such a material, to insulate the shaft from the patient, in particular in the region of the port of entry coincident with the center of rotation. One nonconductive material for the shaft comprises an electrical grade fiberglass/vinyl ester composite material. Alternatively, a shaft of stainless steel or carbon fiber may be coated with, e.g., a nylon or parylene, such as Nylon-11 or Parylene C.

The cables that extend internally along the shaft **416** typically have non-conductive portions **456**. Such non-conductive or insulative portions are typically high strength polymer cables in the form of, e.g., a liquid crystal polymer (LCP) such as VECTRAN, a liquid crystal polyester. The VECTRAN portions are typically crimped to opposed hypotube lengths. Opposed ends of such hypotubes are in turn typically crimped to tungsten cable lengths which extend to the spools in the housing **401** and to the wrist mechanism **850**, respectively.

It will be appreciated that a number of other elements of the tool may also be formed of an insulative material. For example, the pulley arrangement **820**,**820**B and the wrist member **850** coupled to the distal end of the shaft **416** may be formed of an insulative material such as, e.g., ULTEM.

Electro-Surgical End Effectors

Referring now to FIGS. **5**A-**5**B, **6**A-**6**B, and **7**A-**7**B, exemplary cauterizing end effectors are illustrated. U.S. Pat. No. 6,840,938, filed by Morely et al. on Dec. 21, 2001 which has been incorporated by reference illustrates additional embodiments of cauterizing end effectors or electro-surgical end effectors.

FIGS. **5**A-**5**B, illustrate a portion of an exemplary bipolar cauterizing tool **528**. A wrist **574** is rotatably coupled to shaft **562** about the first axis A**1**. End effectors **578**, **580** are rotatably coupled to the wrist **574** about a second axis A**2**. Both the end effectors and the wrist can rotate together about the longitudinal axis A**3** of the shaft **562**. A negative and positive electrode **582**A, **582**B (shown most clearly in FIGS. **6**A and **6**B) can be coupled to the end effectors to deliver a high frequency electrical energy into tissue engaged by the jaws **578**, **580**.

The conductive electrodes **582**A, **582**B can be coupled to an electric power supply (see the bipolar generator **102**A illustrated in FIG. **1**) through conductive leads **584**A, **584**B. In an exemplary embodiment, the conductive leads can be run from the tool base end of the instrument, through the shaft **562**, through lumens in wrist **574**, and up to the electrodes **582**A, **582**B disposed on the end effectors **578**, **580**. The distal portion of the conductive leads **584**A, **584**B can be run outside of the wrist **574** so as to allow for easy connection and disconnection of the conductive leads **584**A, **584**B from the electrodes.

Depending on the specific configuration of the cauterizer, the end effectors **578**, **580** and drive system can be composed of a nonconductive material or a conductive material. In some embodiments, the electrodes can be insulated from the end effector with either a nonconductive bushing or sleeve that is composed of plastic, ceramic, TEFLON, ULTEM, or other non-conductive materials. If the electrodes are attached directly to the end effectors, an insulating bushing can be disposed between the conductive end effectors and the electrodes so that the only "live" portion of the surgical instrument are the electrodes.

The electrodes of the present invention are preferably made of a conductive material such as aluminum, stainless steel, platinum, tungsten, gold, or the like. The electrodes can be in the form of strips, deposited material, inserts, or the like. In some embodiments, the jaws themselves can be the electrodes.

For the bipolar methods of the present invention, the two electrodes on the end effectors should be at two electrical potentials and should not come in contact with each other. Thus, in most embodiments the electrodes are configured to have a gap between the electrodes even when the end effectors are in the closed configuration. As is the case with conventional electrosurgical instruments, a range of supply settings may be used for cutting, coagulation and the like. Moreover, it should be appreciated, that the electrodes can be configured in a wide variety of patterns and designs.

An exemplary power supply can create a wattage up to approximately one-hundred-twenty (120) Watts of power for cauterizing the target tissue. The voltage used with a bipolar robotic cauterizer tool is generally between zero (0) volts (V) and one thousand (1000) V peak-to peak, and preferably

between one-hundred (100) V and five-hundred (500) V. As long as the jaws and electrodes are both in good contact with the tissue intended to be cauterized and/or cut, there is much less chance of voltage from the electrodes arcing to other conductive components on the instrument (e.g., the wrist, shaft, or pulleys). It should be appreciated, however, that the voltage setting of the electrosurgical power generator will vary depending on the specific dimensions of the electrodes, the tissue to be treated, and the like.

In exemplary embodiments, movement of end effectors **578**, **580** are effected through mechanical actuation of a yaw cable **586** and pitch cable **588** via surgeon input devices. Actuation of the pitch cable **588** can rotate the end effectors **578**, **580** about the wrist axis A**1**, while actuation of the yaw cable **586** moves the jaws about axis A**2**, an axis that is substantially perpendicular to axis A**1**, between an open and closed position. Typically, the cables **586**, **588** are directed through lumens in the shaft and wrist body and through a conductive or nonconductive pulley assembly **590**.

As shown in FIGS. **6**A-**7**B, in one configuration the end effectors **578**, **580** include a jaw body **792** and a pivot body **794**. Nonconductive sleeves **696** can be removably coupled to jaw body **792** to attach electrodes **582**A, **582**B to the end effector. As shown, the sleeves **696** include grip surfaces **698** that can contact and grip the target tissue. The electrodes **582**A, **582**B can be molded inserts or a conductive material etched or deposited onto the sleeves. The nonconductive sleeves can include a slot **700** for receiving the jaw body **792** so as to insulate the end effectors from the conductive electrodes. In some configurations, the electrodes and grip surfaces of the jaws can be "non-stick," such as coated with a non-stick polymer, e.g., TEFLON. The conductive leads can be routed through openings **702** in the sleeves **696** and jaw body **792** to contact the electrodes **582**A, **582**B.

The sleeves **696** are preferably disposable so as to allow the physician to replace the sleeves between each surgical procedure, if desired. The conductive leads **584**A, **584**B can also be detachable from the electrodes **582**A, **582**B so as to decouple the electrodes from the power supply. During or after the surgical procedure, the sleeves **696** and the electrodes **582**A, **582**B can be removed from the jaw body **792** and replaced. Thus, different sized electrodes, a different tooth configuration on the end effectors, a different configuration of electrodes, or the like, can be easily attached to the jaw body **792**. In such arrangements, to allow for easy detachment, the conductive leads **584**A, **584**B can be routed through a lumen in the wrist and to an unprotected path outside the wrist. In other embodiments, the jaws **578**, **580**, wrist **574**, and pulleys **590** can be composed of a nonconductive material and the electrodes can be directly coupled to the end effectors. Consequently, non-conductive bushings can be positioned between the end effectors, and nonconductive sleeves that overly the jaw body **792** are not needed.

In exemplary arrangements, as shown most clearly in FIGS. **6**A and **6**B, the first electrode **582**A will be disposed in a groove **604** on the jaw or sleeve and the second electrode **582**B will be disposed on a boss **606**. When the end effectors are moved to the closed position, the boss **606** and groove **604** will interdigitate while still maintaining a gap between the two electrodes. The boss and groove configuration has been found to create thin coagulation heating lines in the tissue when current is delivered between the electrodes. The thin heating lines in the tissue make it easy for the user to cut and separate the tissue by applying a small amount of tension. The time of heating will depend primarily on the size of the tissue being coagulated, the electrode configuration, the current, and the like.

It should be appreciated that the electrodes can be positioned on opposing end effector or on the same end effector. Moreover, the electrodes do not have to be disposed within a groove or on a boss. The electrodes can contact the engaged tissue disposed between the electrodes **582**A, **582**B and a current is applied between the spaced electrodes to deliver a current flow to cauterize the tissue. If desired, a tension force applied from the end effectors can cut the tissue along the cauterization heat lines to separate the tissue. In this case, the jaws can optionally include a cutting blade disposed on the jaws to facilitate cutting of the tissue. The blade can be stationary or spring loaded and may be conductive or nonconductive.

Drive System

Referring now to FIG. **8**, a simplified illustration of a drive system **800** is shown to mechanically couple servomotors **802**A, **802**B to the end effectors **812**A,**812**B, respectively through a set of cables and pulleys. The drive system **800** further mechanically couples servomotor **802**C to move a joint of the wrist **850** of the robotic surgical tool through another set of cables and pulleys. The drive system **800** further still mechanically couples servomotor **802**D to the shaft **416** of the robotic surgical tool through still another set of cables and pulleys.

The drive system **800** includes a tool drive portion **800**A and a robotic surgical arm portion **800**B that are coupled together at an interface **810**. The tool drive portion **800**A corresponds to the drive system in the robotic surgical tool **400**. The robotic surgical arm portion **800**B corresponds to the drive system in the robotic surgical arm **153**.

The tool drive portion **800**A of the drive system **800** receives mechanical inputs from the robotic surgical arm portion **800**B through driven elements **818**A-**818**D, including input disks. From the driven element **818**C, the tool drive portion of the drive system translates mechanical inputs from driven element **818**C into articulation of a wrist member **850** about the first axis A**1**. From the driven elements **818**A-**818**B, the tool drive portion of the drive system translates mechanical inputs from the driven element **818**A-**818**B into articulation of the wrist **850** about the first axis A**2** as well as into actuation of the two element end effectors **812**A,**812**B by relative movement of the end effector elements about axis A**2**. From the driven element **818**D, the tool drive portion of the drive system translates mechanical inputs from driven element **818**D to effect rotation of the end effectors **812**A-**812**B and the wrist **850** about the axis A**3** of shaft **416** by rotating the shaft relative to housing **401** over a limited angle of rotation. In FIG. **8**, the rotational motion of shaft **416** about axis A**3** is omitted in order to more easily show other elements of the system. Care should be taken to prevent over-rotation of the shaft that may cause cables therein to twist into contact with each other and create friction between the cables.

The robotic surgical arm portion **800**B of the drive system **800** includes servomotors **802**A-**802**D that are mechanically coupled to rotatable driver pulleys **828**A-**828**D through cable loops CL**5**-CL**8** to transfer rotation of the servomotors to the rotatable driver pulleys. The servomotors **802**A-**802**D may be standard drive motors having position encoders. However, other actuators may be used, such as hydraulic actuators and piezoelectric motors. To be used as an actuator in the present surgical instrument a drive mechanism should be able to provide variable and controllable force and position control. Capstans **804**A-**804**D are coupled to shafts of the respective servomotors **802**A-**802**D. A pair of ends of each cable loop CL**5**-CL**8** are wrapped within a spiral groove around the

capstans **804**A-**804**D so that one end is payed out as one end is take in. A pair of opposite ends of the cable loops CL**5**-CL**8** are wrapped around opposite sides of a pulley of the rotatable driver pulleys **828**A-**828**D. The cable loops CL**5**-CL**8** may also move over one or more idler pulleys **830**-**840** between the capstans **828**A-**828**D and the rotatable driver pulleys **828**A-**828**D. Additionally, the robotic surgical tool **400** moves along a carriage **237** such that the cable loops CL**5**-CL**8** and one or more idler pulleys **830**-**840** may adjust in position to allow for the movement in the robotic surgical tool which is not shown in the simplified FIG. **8**.

At the interface **810**, the rotatable driver pulleys **828**A-**828**D of the robotic surgical arm portion couple to the driven elements **818**A-**818**D of the tool drive portion **800**A when the robotic surgical tool **400** is mounted to the robotic surgical arm. The driven elements **818**A-**818**D couple to the rotatable driver pulleys **828**A-**828**D respectively through an adapter that is not shown in the simplified FIG. **8**.

When the rotatable driver pulleys **828**A-**828**D of the robotic surgical arm portion couple to the driven elements **818**A-**818**D of the tool drive portion **800**A, the servo motor **802**A can drive the driven pulley **820**A and the end effector **812**A. The servo motor **802**B can drive the driven pulley **820**B and the end effector **812**B. The servo motor **802**C can drive the driven pulley **882** and yaw the wrist **850**. The servo motor **802**D can drive the drum **884** and rotate the shaft to roll the wrist **850**.

Referring back to the tool portion **800**A of the drive system, end effectors **812**A,**812**B; wrist member **850**, and the shaft **416** of the tool **400** are driven by cable loops CL**1**, CL**2**, CL**3**, and CL**4** arranged into an actuation scheme around a plurality of pulleys. The actuation scheme allows the actuation of a three degree-of-freedom wrist using four cable loops. Alternative actuation schemes using more or less cable loops and cables may be desirable in situations where the forces required for actuation of different motions differ greatly in magnitude. Employing cables instead of gears to control the robotic surgical tool **400** minimizes the amount of friction and backlash within instrument. The combination of small moving masses and low friction enables instrument **400** to provide force reflection to the master control computer **151** at the master console **150** with high sensitivity.

Cable loop CL**1** drives end effector **812**A and includes a first cable C**1**A and a second cable C**1**B forming two sides of the cable loop. The first cable C**1**A engages the driven element **818**A at one end in a first direction, wraps over one or more intermediate idler pulleys **870** in the wrist **850**, and couples to the driven pulley **820**A at a second end in a first direction. The second cable C**2**A engages the driven element **818**A at one end in a second direction, wraps over one or more intermediate idler pulleys **876** in the wrist **850**, and couples to the driven pulley **820**A at a second end in a second direction.

Cable loop CL**2** drives end effector **812**B and includes a first cable C**2**A and a second cable C**2**B forming two sides of the cable loop. The first cable C**2**A engages the driven element **818**B at one end in a first direction, wraps over one or more intermediate idler pulleys **872** in the wrist **850**, and couples to the driven pulley **820**B at a second end in a first direction. The second cable C**2**A engages the driven element **818**B at one end in a second direction, wraps over one or more intermediate idler pulleys **874** in the wrist **850**, and couples to the driven pulley **820**B at a second end in a second direction.

Cable loop CL**3** drives a pulley **882** in the wrist **850** to rotate it about axis A**1** and includes a first cable C**3**A and a second cable C**3**B forming two sides of the cable loop. The first cable C**3**A engages the driven element **818**C at one end in a first direction and couples to the driven pulley **882** at a second end in a first direction. The second cable C**3**B engages the driven element **818**C at one end in a second direction and couples to the driven pulley **882** at a second end in a second direction.

Cable loop CL**4** drives a drum **884** in the housing **401** that is coupled to the shaft **416** to rotate it about axis A**3**. Similar to the cable loop CL**3**, the cable loop CL**4** and includes a first cable and a second cable forming two sides of the cable loop that are coupled on opposite sides to each of the drum **884** and the driven element **818**D.

Referring now to FIG. **9**, further details of the drive system **800** for the end effector **812**A is illustrated with respect to the robotic surgical tool **400** and the robotic surgical arm **153**. FIG. **9** is an additional schematic diagram illustrating the drive system for one of the two end effectors. Servomotor **802**A is mechanically coupled by the drive system **800** to the end effector **812**A through a series of cables and pulleys.

Cables C**5**A-**05**B of the cable loop CL**5** mechanically couple the servomotor **802**A to the rotatable driver pulley **828**A in the robotic surgical arm **153**. The capstan **804**A is coupled to the drive shaft **904**A of the servomotor **802**A. A pair of ends of the cable loop CL**5** are wrapped within a spiral groove around the capstan **804**A so that one end of the cable C**5**A is payed out as one end of cable C**5**B is taken in and visa-versa. The pair of ends at the opposite end of the cable loop CL**5** are wrapped around opposite sides of the pulley **928**A of the rotatable driver pulley **828**A to match the linear direction of the cables C**5**A-**05**B, as one is taken up the other is payed out. The cable loop CL**5** may also move over one or more idler pulleys **831**-**832** between the capstan **804**A and the pulley **928**A of the rotatable driver pulley **828**A. Through the cable loop CL**5**, capstan **804**A, and pulley **928**A, the rotation of the servomotor **802**A is mechanically coupled to the rotatable driver pulley **828**A.

The rotatable driver pulley **828**A mechanically couples to the input disk **918**A of the driven element **818**A by means of a rotatable adapter **910**A at the interface **810**.

In the robotic surgical tool **400**, cables C**1**A-C**1**B of the cable loop CL**1** mechanically couple the driven element **818**A to the driver pulley **820**A and its end effector **812**A. One end of each of the cables C**1**A-C**1**B of the cable loop CL**1** wrap around and couple to the actuating spool **920**A of the driven element **818**A. The opposite end of each of the cables C**1**A-C**1**B of the cable loop CL**1** wrap around opposite sides and couple to the driven pulley **820**A. The cable loop CL**1** may also move over one or more idler pulleys **870** between the input disk **918**A and the pulley **820**A. Through the cable loop CL**1**, input disk **918**A, and pulley **820**A, the rotation of the driven element **818**A is mechanically coupled to the pulley **820**A and the end effector **812**A.

Generally, rotation of the elements **818**A-**818**D in a first direction causes the pulleys to rotate in a first direction by pulling on a first side of the cable loop and paying out the second side of the cable loop. Rotation of the elements **818**A-**818**D in a second direction causes the pulleys to rotate in a second direction by pulling on the second side of the cable loop and paying out the first side of the cable loop.

In the tool portion **800**A, the amount of rotation of the driven elements **818**A-**818**D that is transferred into rotation at the axes A**1**-A**3** is a function of the radius of the actuating spools (such as spool **920**A) at the driven elements, about which the cables wrap at one end, and the radius of the driven pulleys **820**A,**820**B, **882** and drum **884** at the second end. Actuating spools can be chosen with differing radius at the driven elements **818**A-**818**C to obtain more or less rotation in the driven members given that the driven pulleys **820**A,**820**B, **882** are often constrained by size limitations at the distal end

of the shaft **416** of the robotic surgical tool. However, with larger shaft diameters the radius of the driven pulleys **820**A, **820**B, **882** can be increased to provide a greater range of motion and force. Additionally, the radius of the driven pulleys **820**A,**820**B, **882** may be chosen to allow the cables to properly engage idler pulleys. For example, driven pulleys **820**A-**820**B may have different diameters in order to allow their cables to suitably engage their respective intermediate idler pulleys. Additionally, the radius of idler pulleys may be chosen to keep the cables they are guiding straight but are preferably small to minimize space requirements.

At the interface **810**, the ratio of the radius of rotatable driver pulleys **828**A-**828**D to the radius of the actuating spool of the driven elements **818**A-**818**D acts like a transmission. The ratio of these radiuses change the amount of linear distance of cable that is pulled in and payed out at the actuating spool in the robotic surgical tool from that of the linear distance of cable that is pulled in and payed out at the rotatable driver pulleys **828**A-**828**D.

In the robotic surgical arm portion **800**B, the amount of rotation of the capstans **818**A-**818**D at the motors **802**A-**802**D that is transferred to the rotatable driver pulleys **828**A-**828**D is a function of the radius of the capstans **818**A-**818**D and the radius of the rotatable driver pulleys **828**A-**828**D. As these elements are found in the robotic surgical arm, their radius are constant for each type of tool that is mounted to the robotic surgical arm.

For the servomotors **802**A-**802**B to drive the end effectors **812**A-**812**B, a torque differential coupling matrix may be used to provide a translation of torque at the servomotors to the driven pulleys **802**A-**820**B about their respective axis. For the servomotors **802**C-**802**D to respectively drive the driver pulley **882** and the drum **882**, the coupling matrix is also used to translate a torque at the servomotors to the driven pulley **882** and drum **884** about their respective axis. At the end effectors **812**A-**812**B, the torque at the driven pulleys **802**A-**802**B can be simply converted into a linear force at tips of the end effectors knowing the radius of the pulleys and the length of the end effectors extending beyond the pulleys. This linear force at the tips of the end effectors is often referred to as a tip force which is further described with reference to FIG. **11** below.

Referring now to FIG. **10**, three cable loops CL**1**, CL**2**, CL**3** are used to effect movement of the wrist mechanism **850** as previously discussed. Cable loops CL**1** and CL**2** are used to effect movement in the end effectors **812**A,**812**B about the pivotal connection or pin **1060**. It will be appreciated that four cables may extend through the wrist-like member to effect movement in the end effectors **812**A,**812**B, although fewer cables would be required for a single-finger end effector. Cable loop CL**3** is used to effect movement in the wrist **850** about the pivotal connection or pin **1054**.

One end of each cable C**1**A,C**1**B of the cable loop CL**1** is anchored to the drive pulley **820**A to effect movement in the end effector **812**A about the pivotal pin **1060**. One end of each cable C**2**A,C**2**B of the cable loop CL**2** is anchored to the drive pulley **820**B to effect movement in the end effector **812**B about the pivotal pin **1060**. One end of each cable C**3**A,C**3**B of the cable loop CL**3** is anchored to the drive pulley **882** to effect movement in the wrist **850** about the pivotal pin **1054**.

As previously discussed, one or more idler pulleys may be used to route the cable loops CL**1**, CL**2** through the wrist **850** to the respective driven pulleys **820**A-**820**B.

The cable of the cable loop CL**1** rides over an outer idler pulley **870** of the first pulley set and an outer idler pulley in the second pulley set **1068** and into a circumferential channel in the driven pulley **802**A over the first cable portion C**1**A. From the driven pulley **802**A, the cable of the cable loop CL**1** exits from the circumferential channel in the driven pulley **802**A rides over an inner idler pulley in the third pulley set **1070** and the inner idler pulley **876** in the fourth pulley set over the second cable portion C**1**B.

The cable of the cable loop CL**2** rides over an inner idler pulley **872** of the first pulley set and an inner idler pulley in the second pulley set **1068** and into a circumferential channel in the driven pulley **802**B over the first cable portion C**2**A. From the driven pulley **802**B, the cable of the cable loop CL**2** exits from the circumferential channel in the driven pulley **802**B rides over an outer idler pulley in the third pulley set **1070** and the outer idler pulley **874** in the fourth pulley set over the second cable portion C**2**B.

To use the end effector **812**A, when cable C**1**A is pulled in the direction of arrow A**1**, cable C**1**B is payed out and the end effector **812**A is caused to displace angularly about the pivotal connection **1060** in the direction of arrow S**1**. If cable C**1**B is pulled in the direction of arrow A**2**, cable C**1**A is payed out and the end effector **812**A is caused to displace angularly about the pivotal connection **1060** in the direction of arrow S**2**.

To use the end effector **812**A, when cable C**2**A is pulled in the direction of arrow B**1**, cable C**2**B is payed out and the end effector **812**B is caused to displace angularly about the pivotal connection **1060** in the direction of arrow R**1**. When cable C**2**B is pulled in the direction of arrow B**2**, cable C**2**A is payed out and the end effector **812**B is caused to displace angularly about the pivotal connection **1060** in the direction of arrow R**2**.

Thus to coincidentally close the jaws of the end effectors **812**A-**812**B together without any wrist movement, cable C**1**B is pulled in the direction of arrow A**2** and cable C**2**A is pulled in the direction of arrow B**1** simultaneously. To coincidentally open the jaws of the end effectors **812**A-**812**B together without any wrist movement, cable C**1**A is pulled in the direction of arrow A**1** and cable C**2**B is pulled in the direction of arrow B**2** simultaneously.

Furthermore, the orientation of the end effectors **812**A-**812**B may be moved together as a whole in the same direction relative to the wrist member **52**, as indicated by the arrows T**1** and T**2**. In this case, cable C**1**A is pulled in the direction of arrow A**1** and cable C**2**A is simultaneously pulled in the direction of arrow B**1** so as to displace both end effectors **812**A-**812**B in the direction of arrow T**1**. Similarly, to move the end effectors **812**A-**812**B in the direction of arrow T**2**, C**1**B is pulled in the direction of arrow A**2** and cable C**2**B is simultaneously pulled in the direction of arrow B**2**.

All of the tension in the activation cables C**1**A,C**1**B,C**2**A, C**2**B, in the surgical tool may not be transferred into a force at the tip of the end effectors **812**A, **812**B due to the small sizes of the pulleys coupled to the end effectors.

Referring now to FIG. **11**, a simplified schematic diagram illustrates the force transmission that may be provided by a pair of jaws of end effectors **812**A-**812**B such as a gripper to tissue. As discussed previously, the end effectors **812**A-**812**B are coupled to driven pulleys **820**A-**820**B respectively and may be rotated about the axis A**2**. The pulleys **820**A-**820**B are respectively driven by the cable loops CL**1**-CL**2**.

TO is the cable tension in the activation cable loop CL**2** for the end effector **812**B. T**1** is the cable tension in the activation cable loop CL**1** for the end effector **812**A. R**0** and R**1** are the respective radii of the pulleys about which the jaws rotate of the end effector. L**0** and L**1** are the respected distances from the center axis of the pulleys to the tip of the jaw. F**0** and F**1** are the respective forces applied at the tips of the jaws and are proportional to the cable tensions TO and T**1**. The ratios

R0/L0 and R1/L1 may reduce the respective forces F0 and F1 that is to be generated by the tensions T0 and T1 respectively. This is because the ratios R0/L0 and R1/L1 may often be less than one and typically are less than 0.5. While techniques of obtaining a mechanical advantage may increase the ratios at the end effectors, such as those described in U.S. Pat. No. 6,206,903 by Ramans, with any reduction in transferring the cable tension to the tip force, it is important to drive the maximum possible tension into the cables of the robotic surgical tool.

While a particular embodiment of a drive system **800** has been described, possible changes to the configuration of pulleys, cables and motors described above will be apparent to those of skill in the art. For example, an alternate tool drive portion for the drive system is described in U.S. Pat. No. 5,792,135, the full disclosure of which is incorporated herein by reference. The choice of the particular drive scheme employed in a particular embodiment will depend on the constraints of the forces required to be exerted by the instrument and the need to reduce the inertia and friction of the parts of the instrument that move during its actuation. For example, a wide variety of alternative drive systems might be employed, including alternative cabling arrangements, drive chains or belts, hydraulic drive systems, gear trains, rods, wire, or the like. In some of these drive systems, motion of end effectors **812**A-**812**B about the axes may be coupled to multiple driven elements **818**. In other embodiments, there may be a one to one correspondence between driven elements **818** and motion of an end effector element about an axis. Still other embodiments may require fewer (or more) driven elements to effect the desired degrees of freedom, for example, when a single element end effector is provided. Hence, manipulation of the end effector via interface **810** will generally involve some reconfiguration of the robotic system during the tool change, such as through the coupling matrix described previously.

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Referring now to FIG. **12**A, a top view of the tool base **412** is illustrated with cover removed to show the driven elements **818**A-**818**D and the cables C1A-C1B, C2A-C2B, C3A-C3B, and C4A-C4B of the respective cable loops CL1, CL2, CL3, and CL4 shown in FIG. **8**. The driven elements **818**A-**818**C each include an input disk **918**A-**918**C and an actuation spool.

Referring now to FIG. **12**B, a side view of the driven element **818**A is illustrated that is also representative of the driven elements **818**B-**818**C. The driven element **818**A includes the input disk **918**A, a drive shaft **1210** coupled to the input disk, and the actuating spool **920**A coupled to the drive shaft. The input disk includes pins **1218** to mate with the adapter **910**A of the interface. The drive shaft **1210** extends up through an opening in the tool base **412** into the interior of the mountable housing. The actuating spool **920**A includes an upper clamping pulley **1220**U and a lower clamping pulley **1220**L. Each of the upper clamping pulley **1220**U and the lower clamping pulley **1220**L have a first clamp half **1221**A and a second clamp half **1221**B. A pair of fasteners **1222** couples the first clamp half **1221**A to the second clamp half **1221**B and each clamping pulley **1220**U,**1220**L to the drive shaft **1210**. The cable C1B is wrapped around in a spiral groove and coupled to the upper clamping pulley **1220**U. The cable C1A is wrapped around in a spiral groove and coupled to the lower clamping pulley **1220**L.

With each of their fasteners **1222** being loose, the upper clamping pulley **1220**U and the lower clamping pulley **1220**L may turn independently of each other about the drive shaft **1210**. The upper clamping pulley **1220**U and the lower clamping pulley **1220**L can be used to assist in the initial assembly of the cable loop CL1 through the robotic tool to the driver pulley **820**A and the alignment of the end effector **812**A. The upper clamping pulley **1220**U and the lower clamping pulley **1220**L can also be used to initially set and later adjust the tension in the cables C1A-C1B of the cable loop CL1 between the driver pulley **820**A and the actuating spool **920**A.

The ends of the cables C1A-C1B of the cable loop CL1 are wrapped around the clamping pulleys **1220**U-**1220**L in their respective spiral grooves so that one end pays out while the other end is taken in and visa-versa. If the input disk is rotated in the direction of arrow R1, cable C1A may be taken in as indicated by arrow TI_1 and cable C1B may be payed out as indicated by arrow PO_1. If the input disk is rotated in the opposite direction as indicated by arrow R2, cable C1B may be taken in as indicated by arrow TI_2 and cable C1A may be payed out as indicated by arrow PO_2.

Referring now back to FIG. **12**A, the driven element **818**D has a different type of actuation spool but operates similarly so that cable C4A of cable loop CL4 is taken in while cable C4B of the cable loop CL4 is payed out and visa versa. An end of the cables C4A and C4B of the cable loop CL4 wrap around the drum **884** to rotate the shaft **416**.

The cables C2A,C2B of the cable loop CL2 and cables C3A,C3B of the cable loop CL3 respectively ride on first and second pairs of stacked idler pulleys **1201** in the tool base **412** before entering the shaft **416**. The cables C1A,C1B of the cable loop CL1 ride on a pair of stacked idler pulleys **1202** in the tool base **412** before entering the shaft **416**.

As discussed previously in reference to the drive system **800**, the cables C1A,C1B of the cable loop CL1 drive the end effector **812**A and the cables C2A,C2B of the cable loop CL2 drive the end effector **812**B. In a typical robotic surgical tool **400**, rotating the driven elements **818**A,**818**B and the respective input disks **918**A,**918**B in opposite directions respectively closes the jaws or end effectors **812**A,**812**B together as illustrated by the arrows **1200**A-**1200**B indicating the close rotational direction. Input disk **918**A may be referred to as input disk six. Input disk **918**B may be referred to as input disk seven.

Referring now to FIGS. **13**A-**13**C, FIGS. **14**A-**14**D, and FIGS. **15**A-**15**C, the operation of closing the end effectors **812**A-**812**B from an open position to drive to maximum torque is now described. FIGS. **15**A-**15**C illustrate the operation of the master grips **350**A-**350**B around the touch sensitive handle **325** in the master console **150** in the context of grip space. That is, the actual angular position θ^a_M of the master grips **350**A-**350**B is provided to the servomechanism control system (see FIGS. **18**A-**18**B) to drive the input disks and the end effectors **812**A,**812**B. FIGS. **13**A-**13**C illustrate the operation of the input disks **918**A-**918**B in the robotic surgical tool at the interface **810** in the context of disk space. The input disks **918**A-**918**B physically rotate over angles in disk space in response to the servo-motors **802**A-**802**B and the motor torque input thereto. FIGS. **14**A-**14**D illustrate the operation of the end effectors **812**A-**812**B in the robotic surgical tool in the context of wrist space at the wrist **850**. The desired angular position θ^d_S of the slave end effectors **812**A-**812**B in wrist space is derived as a function of the actual angular position θ^a_M of the master grips **350**A-**350**B in grip space. The desired angular position θ^d_S of the slave end effectors **812**A-**812**B is processed by the servomechanism control system in an attempt to make the difference between the desired angular position θ^d_S and the actual angular position

θ^a_s of the slave end effectors **812**A-**812**B be zero. The servomechanism control system may also take into account the velocity of the master grips in forming a joint torque as is described below with reference to FIGS. **18**A-**18**B.

Referring now to FIGS. **13**A, **14**A, **15**A, and **20**A, the master grips **350**A-**350**B are substantially open having a large positive actual angular position θ^a_M at a point W, for example, on the curve **2002** illustrated in FIG. **20**A. The function f(.) as is discussed further below and exemplary illustrated in FIG. **20**A, is used to determine the desired end effector slave angle θ^d_s. The servomechanism drives the input disks **918**A-**918**B to a first position **918**A'-**918**B' with the jaws or end effectors **812**A-**812**B being open as illustrated in FIG. **14**A. The jaws or end effectors **812**A-**812**B are at a first actual end effector slave angle θ^a_s which is congruent to the positive desired end effector slave angle θ^d_s. Note that as the master grips **350**A-**350**B are closed from this position, the input disks **918**A, **918**B are rotated in the respective close directions **1200**A-**1200**B and the end effectors **812**A-**812**B close in the direction of arrows S**2** and R**1**, respectively.

Referring now to FIGS. **13**B, **14**B, **15**B, and **20**A, the master grips **350**A-**350**B are closed to a point where the end effectors **812**A-**812**B just make contact. The actual master angular position θ^a_M is at a point O, zero degrees for example, on the curve **2002** illustrated in FIG. **20**A. The function f(.), such as that illustrated in FIG. **20**A, may be used to determine the desired end effector slave angle θ^d_S. At the position O on curve **2002**, with the master angular position θ^a_M being zero degrees for example, the desired end effector slave angle θ^d_S is zero degrees as well. The servomechanism drives the input disks **918**A-**918**B so they are rotated in their respective close directions **1200**A-**1200**B to a second position **918**A"-**918**B", that may be referred to as a disk bumper position, where the jaws or end effectors **812**A-**812**B just touch together as illustrated in FIG. **14**B. The jaws or end effectors **812**A-**812**B are at a second actual end effector slave angle θ^a_s of substantially zero degrees that is congruent to the positive desired end effector slave angle θ^d_S.

With the input disks at the respective disk positions **918**A"-**918**B", the jaws or end effectors **812**A-**812**B are substantially at an actual slave angle θ^a_s of zero degrees with little to no force being applied at tips of the end effectors when they just touch together or just touch tissue. The end effectors **812**A-**812**B may be closed a little further on tissue S in a surgical site and then have a tip force F_m applied to the tissue to cauterize or seal it together. While the jaws or end effectors **812**A-**812**B may not actually move much more, such that the actual end effector slave angle remains substantially the same, additional torque can be generated at the driven pulleys **820**A-**820**B so that the tip force Fm may be generated. Referring now to FIGS. **13**C, **14**C, **14**D, **15**C, and **20**A, the master grips **350**A-**350**B are closed to a substantially closed position. The actual master angular position θ^a_M is a negative number at a point P', negative five degrees for example, on the curve **2002** illustrated in FIG. **20**A. The function f(.), such as that illustrated in FIG. **20**A, may be used to determine the desired end effector slave angle θ^d_s. At the point P' on curve **2002**, with the master angular position θ^a_M being negative five degrees for example, the desired end effector slave angle θ^d_s may be negative 35 degrees for example.

A desired end effector slave angle θ^d_s that has a negative value is theoretically illustrated in FIG. **14**D by the end effectors **812**A-**812**B crossing over one another. However, the end effectors **812**A-**812**B do not actually cross over one another. Instead, the actual end effector slave angle θ^a_s substantially differs from the desired end effector slave angle θ^d_s as can be seen by a comparison of FIGS. **14**C and **14**D. While the actual end effector slave angle θ^a_s remains substantially close to zero degrees, the torque applied at the joint of the end effectors **812**A-**812**B has increased significantly. This is because the servomechanism continues to try and drive the end effectors **812**A-**812**B so that the actual end effector slave angle θ^a_s become congruent to the negative value of the desired end effector slave angle θ^d_s. As the end effectors **812**A-**812**B may not cross over one another, the actual end effector slave angle θ^a_s will not become congruent to the negative value of the desired end effector slave angle θ^d_s. Thus, with the master grips at their substantially closed position, the servomechanism continues to try and drive the end effectors **812**A-**812**B to the negative value of the desired end effector slave angle θ^d_s unless it is limited by maximum torque values or a physical limitation in the cable drive system **800** of the robotic surgical arm **153** and/or the robotic surgical tool **400**.

In FIG. **13**C, the input disks **918**A-**918**B are further rotated in their respective close directions **1200**A-**1200**B to a third position **918**A'"-**918**B'" through a maximum torque angle of rotation θ_{TmaxA} and θ_{TmaxB}, respectively where maximum torque is applied to the tissue S by the servomechanism being limited to a maximum torque limit. Robotic surgical tools may have different values of θ_{TmaxA} and θ_{TmaxB} for each input disk **918**A,**918**B to generate a maximum torque at the pulleys **820**A,**820**B after the tips touch. This may be due to differences in cable drive systems and general instrument friction or the desire to apply a varying force to the tissue.

As illustrated in FIG. **14**C, the jaws or end effectors **812**A-**812**B have an actual end effector slave angle θ^a_s that remains at a substantially zero degrees but now has a tip force Fm generated at the tip of the end effectors **812**A-**812**B. As the instrument jaws or end effectors **812**A-**812**B come in contact to a common object, such as the tissue S, the input disks **918**A,**918**B continue to rotate, applying tension to the cables C**1**B and C**2**A of the respective cable loops CL**1** and CL**2**, for example, even though there is little movement of the end effectors **812**A-**812**B. The tension on the cables C**1**B and C**2**A of the respective cable loops CL**1** and CL**2** translates into maximum torque at the end effectors **812**A-**812**B and a tip force Fm for gripping tissue within the jaws of the end effectors **812**A-**812**B.

The input disks **918**A-**918**B have rotated from their second positions (which may be referred to as a disk bump position) until a pre-determined maximum torque setting has been reached or the user releases the master grip driving the input disks. Previously a maximum rotational position limit in wrist space could have limited the rotation of the input disks **918**A-**918**B so that the maximum torque setting would not be reached with stretched cables. For example, consider the function f(.) illustrated by curve **2001** in FIG. **20**A. The point P on curve **2001**, a maximum rotational position limit in wrist space when the master grips **350**A-**350**B are fully closed, may not provide enough torque to drive the end effectors to a maximum joint torque.

In the embodiments of the invention, the maximum rotational position limit in wrist space is extended so that sufficient torque can be generated to drive the end effectors to the maximum joint torque limits. For example, curve **2001** may be used for the function f(.) so that the point P', a maximum rotational position limit in wrist space when the master grips **350**A-**350**B are fully closed, provides enough torque to drive the end effectors to a maximum joint torque. The gain constant K_p for converting angular distance of the grip to a portion of the desired torque value at the joint may additionally or alternatively be increased to K_p, to saturate the torque limit sooner as the master grips **350**A,**350**B are closed rather than

later to drive to maximum torque limits. The increase in the gain constant K_p, is described further below with reference to FIGS. **18**A-**18**B.

With the control system limitation being removed, the physical limitations of the cable drive system **800** may still limit the rotation of the input disks **918**A-**918**B in disk space. In FIG. **13**C, physical limitations of the cable drive system **800** may limit the rotation of the input disks **918**A-**918**B to their physically limited angles of rotation θ_{PLA} and θ_{PLB}, respectively. As illustrated, the physically limited angles of rotation θ_{PLA} and θ_{PLB} are well beyond the expected maximum torque angles of rotation θ_{TmaxA} and θ_{TmaxB}. The servomechanisms may drive the input disks **918**A-**918**B so that the angles θ_{TmaxA} and θ_{TmaxB} may go as high as θ_{PLA} and θ_{PLB}, the physical limit in the range of motion in robotic surgical tool and the robotic surgical arm. However, if driving to the maximum joint torque and a physical limit is reached, a cable is well beyond the expected cable stretch, up to a point where the cable should be replaced before it breaks. That is, over the life of the cables in the tool, when driving to the maximum torque setting, a physical limit of the position of the input disks should never be reached or else the tool should be replaced or repaired.

In one embodiment of the invention it has been determined by experimentation that after the cables have stretched, that a desired end effector slave angle θ^d_s of negative seventy degrees in wrist space with the master grips being substantially closed, will ensure that a maximum torque at the pulleys **820**A,**820**B will always be reached over the life of a robotic surgical tool or instrument.

As discussed previously, the servomechanism continues to try and drive the end effectors **812**A-**812**B to the negative value of the desired end effector slave angle θ^d_s when the master grips **350**A-**350**B are at their substantially closed position unless limited by maximum torque values. The servomechanism is limited by an upper torque limit (UTL) and a lower torque limit (LTL). As the joint torque is a large negative value when trying to reach the negative value of the desired end effector slave angle θ^d_s, the lower torque limit limits the joint torque value generated by the servomechanism.

In one embodiment of the invention, a lower torque limit setting of 0.39 Nm for the servomechanism yielded a measured tip force Fm at the tips of end effectors **812**A-**812**B of approximately 3.4 pounds (lbs). In another embodiment of the invention with a differing jaw length, a lower torque limit setting of 0.14 Nm for the servomechanism yielded a measured tip force of approximately 1.4 lbs. The amount of force applied to tissue may be desirable for certain surgical procedures such as sealing tissue and vessels, and can vary between tool types.

Control System for Master/Slave Robotic Surgical Systems

FIG. **16**A schematically illustrates a block diagram of a control architecture **1600** for a master/slave robotic system that may be executed by the computer **151** in the master console **150**. The control architecture **1600** includes a bilateral controller **1605** to interface between the master control at the master console **150** ("Master Manipulator" **1602**) and the slave control at the robotic surgical arm **153** ("Slave Manipulator" **1608**). The control architecture **1600** may feed forward control inputs from the human operator **1601** to the slave manipulator **1608** in the surgical environment **1609** and may feed back a force as well as sensor information to the master manipulator **1602** and the human operator **1601**.

The human operator **1601**, such as a surgeon, moves an input device of a master manipulator **1602** by applying manual or human forces f_h against the input device. One such input device are the grips **35**A-**350**B. Encoders of master manipulator **1602** generate master encoder signals e_m which are interpreted by a master input/output processor **1603** to determine the master joint positions θ_m ("theta sub m"). The master joint positions are used to generate Cartesian positions x_m of the input device of the master using a master kinematics model **1604**. The Cartesian positions x_m of the input device are coupled into the bilateral controller **1605**.

In the surgical environment **1609**, the tissue structures in the surgical workspace can impose environmental forces f_e against a surgical end effector (and possibly against other elements of the tool and/or manipulator). The environmental forces f_e from the surgical environment **1609** alter the position of the slave manipulator **1608**, which are read by an encoder as slave encoder values e_s which are transmitted to the slave input/output processor **1607**. The slave input/output processor **1607** interprets the slave encoder values e_s to determine joint positions θ_s. The joint positions θ_s are then used to generate Cartesian slave position signals x_s according to the slave kinematics processing block **1606**. The slave position signals x_s are coupled into the bilateral controller **1605**.

The bilateral controller **1605** uses the input master and slave Cartesian positions x_m, x_s to generate the desired Cartesian forces to be applied by the slave f_s so that the surgeon can manipulate the slave manipulator **1608** as desired to perform a surgical procedure. Additionally, bilateral controller **1605** uses the Cartesian master and slave positions x_m, x_s to generate the desired Cartesian force feedback f_m that is coupled into the master so as to provide force feedback to the surgeon.

In general, bilateral controller **1605** generates the slave and master forces f_s,f_m by mapping the Cartesian position of the master in the master controller workspace with the Cartesian position of the end effector in the surgical workspace according to a transformation. Preferably, the control system **1600** will derive the transformation in response to state variable signals provided from the imaging system so that an image of the end effector in a display appears substantially connected to the input device. These state variables will generally indicate the Cartesian position of the field of view from the image capture device, as supplied by the slave manipulators supporting the image capture device. Hence, coupling of the image capture manipulator and slave end effector manipulator is beneficial for deriving this transformation. Bilateral controller **1605** may be used to control one or more robotic surgical arms **153** and the robotic surgical tools **400** coupled thereto. Bilateral controller **1605** may also be provided with additional input signals such as various types of sensors encoders, tachometers, and current-meters, for example.

Based generally on the difference in position between the master and the slave in the mapped workspace, bilateral controller **1605** generates a Cartesian slave force f_s to urge the slave to follow the position of the master. The slave kinematics **1606** are used to interpret the Cartesian slave forces f_s to generate joint torques τ_s ("tau sub s") of the slave which will result in the desired forces at the end effector. Slave input/output processor **1607** uses these joint torques to calculate slave motor currents i_s, which reposition the slave manipulator **1608** at slave position x_e within the surgical worksite.

The desired feedback forces from bilateral controller are similarly interpreted from Cartesian force on the master f_m based on the master kinematics **1604** to generate master joint torques τ_s. The master joint torques are interpreted by the master input/output controller **1603** to provide master motor

current i_m to the master manipulator **1602**, which changes the position x_h of the hand held input device in the surgeon's hand.

It will be recognized that the control system **1600** illustrated in FIG. **16**A is a block diagram simplification. For example, the surgeon does not only apply forces against the master input device, but also moves the handle within the master workspace. Similarly, the motor current supplied to the motors of the master manipulator may not result in movement if the surgeon maintains the position of the master controller. Nonetheless, the motor currents do result in tactile force feedback to the surgeon based on the forces applied to the slave by the surgical environment. Additionally, while Cartesian coordinate mapping is preferred, the use of spherical, cylindrical, or other reference frames may provide at least some of the advantages of the invention.

Referring now to FIG. **16**B, the control system of the robotic surgical system will now be described in greater detail. The control system in FIG. **16**B is generally referenced by the reference number **1610**. A feed forward control section **1675** of the control system **1610** is of interest in explaining how the slave end effectors are driven by the master. The remaining feedback portion of the control system **1610** may be only of interest if a force feedback is to be applied to the master. Typically a simplified biasing feedback is utilized to provide some tactile feedback to the operation of the system such that the feedback portion of the control system **1610** may not be implemented

The master control **1650** has sensors, e.g., encoders, or potentiometers, or the like, associated therewith to enable the control system **1610** to determine the position of the master control **1650** in joint space as it is moved from one position to a next position on a continual basis during the course of performing a surgical procedure. In FIG. **16**B, signals from these positional sensors are indicated by arrow **1614**. Positional and velocity readings measured by the sensors **1687** are read by the input processing **1689** by the processor. It will be appreciated that since the master control **1650** includes a plurality of joints connecting one arm member thereof to the next, sufficient positional sensors are provided on the master **1650** to enable the angular position of each arm member relative to the arm member to which it is joined to be determined thereby to enable the position and orientation of the master frame on the master to be determined. As the angular positions of one arm member relative to the arm member to which it is joined is read cyclically by the processor **1689** in response to movements induced on the master control **1650** by the surgeon, the angular positions are continuously changing. The processor at **1689** reads these angular positions and computes the rate at which these angular positions are changing. Thus, the processor **1689** reads angular positions and computes the rate of angular change, or joint velocity, on a continual basis corresponding to the system processing cycle time, for example 1300 Hz. Joint position and joint velocity commands thus computed at **1689** are then input to the Forward Kinematics (FKIN) controller **1691**.

At the FKIN controller **1691**, the positions and velocities in joint space are transformed into corresponding positions and velocities in Cartesian space. The FKIN controller **1691** is a processor which typically employs a Jacobian (J) matrix to accomplish this. It will be appreciated that the Jacobian matrix transforms angular positions and velocities into corresponding positions and velocities in Cartesian space by means of conventional trigonometric relationships. Thus, corresponding positions and velocities in Cartesian space, or Cartesian velocity and position commands, are computed by the FKIN controller **1691**.

The velocity and the position in Cartesian space is input into a scale and offset converter **1622**. The velocity and the position in Cartesian space may also be input into a Cartesian controller **1620** if force feedback is to be provided.

The minimally invasive surgical apparatus provides for a scale change between master control input movement and responsive slave output movement. Thus, a scale can be selected where, for example, a 1-inch movement of the master control **1650** is transformed into a corresponding responsive ⅕-inch movement on the slave. At the scale and offset step **1622**, the Cartesian position and velocity values are scaled in accordance with the scale selected to perform the surgical procedure. Naturally, if a scale of 1:1 has been selected, no change in scale is effected at **1622**.

After a scale and offset step is performed at **1622**, a resultant desired slave position and desired slave velocity in Cartesian space is input to a simulated or virtual domain at **1612**, as indicated by arrows **1611**. It will be appreciated that the labeling of the block **1612** as a simulated or virtual domain is for identification only and that the simulated control may be performed by elements outside of the functional block **1612**.

The steps imposed on the desired slave velocity and position in the virtual domain **1612** are now generally described. A current slave position and velocity is continually monitored in the virtual or simulated domain **1612**. The desired slave position and velocity is compared with the current slave position and velocity. Should the desired slave position and/or velocity as input from **1622** not cause transgression of limitations, e.g., velocity and/or position and/or singularity, and/or the like, as set in the virtual domain **1612**, a similar Cartesian slave velocity and position is output from the virtual domain **1612** and input into an inverse scale and offset converter **1626**. The similar velocity and position output in Cartesian space from the virtual domain **1612** is indicated by arrows **1613** and corresponds with actual commands in joint space output from the virtual domain **1612** as indicated by arrows **1615**.

As mentioned, the control system **1610** enables limitations to be set in the simulation block **1612**. These limitations can be chosen to conform with mechanical system limitations or constraints and/or can be preset to correspond with environmentally-sensitive movement limitations at the surgical site as will be described in greater detail herein. Thus, the limitations imposed in the simulated domain **1612**, in one instance, can be regarded as virtual limitations corresponding with actual physical system limitations. The limitations at the simulated domain **1612** are not derived from actual slave movement but from simulated or virtual slave movement. Thus, the slave is prevented from actually transgressing a limitation by simulating its movement and velocity and restricting the simulated movement and velocity before instructing the actual slave to respond.

The resultant desired slave joint velocity and position signal from the simulated domain **1612** are passed to a joint controller **1648**. At the joint controller **1648**, the resultant or desired joint velocity and position signal are compared with the current actual joint position and velocity. The current actual joint position and velocity is derived through the sensors **1649** on the slave **1698** after having been processed by processor **1651** to yield slave current position and velocity in joint space.

The joint controller **1648** computes the torques desired on the slave motors to cause the slave to follow the resultant joint position and velocity signal taking its current actual joint position and velocity into account. The joint torques so deter-

mined are then routed to an output processor **1654**. The joint torques may also be coupled to a feedback processor **1652**, if available.

The joint torques are typically computed, by way of example, by means of the formula $\tau_J = K_p \Delta\theta_p + K_v \Delta\theta_v$ where K_p is a spring constant, K_v is a damping constant, $\Delta\theta_v$ ("delta theta v") is the error or difference between the actual joint velocity input and the desired velocity input to the joint controller **1648**, and $\Delta\theta_p$ is the error or difference between the actual joint position input and the desired joint position input to the joint controller **1648**.

The output processor **1654** determines the electrical currents to be supplied to the motors **1655** associated with the slave **1698** to yield the commanded torques and causes the currents to be supplied to the motors as indicated by arrow **1655**.

As mentioned earlier, the slave indicated at **1698** is provided with a plurality of sensors. These sensors are typically operatively connected to pivotal joints on the robotic arm **153** and at the motors driving the robotic surgical tool. One or more sensors may be operatively coupled to joints or other elements of the robotic surgical tool or instrument **400**.

These sensors are operatively linked to the processor at **1651**. It will be appreciated that these sensors determine current slave position. Should the slave **1698** be subjected to an external force great enough to induce reactive movement on the slave **1698**, the sensors will naturally detect such movement. Such an external force could originate from a variety of sources such as when the robotic arm **153** is accidentally knocked, or knocks into another robotic arm **153** or an endoscope arm, or the like.

As mentioned, the joint controller **1648** computes torques desired to cause the slave **1698** to follow the master **1650**. An external force on the slave **1698** which causes its current position to vary also causes the desired slave movement to follow the master to vary. Thus a compounded joint torque is generated by the joint controller **1648**, which torque includes the torque desired to move the slave to follow the master and the torque desired to compensate for the reactive motion induced on the slave by the external force. The torque generated by the joint controller **1648** may be routed to the feedback processor at **1652**, if a force feedback system is to be provided.

End Effector Control for Maximizing Torque Drive

Referring now to FIG. **17**, a block diagram of a master/slave servomechanism arrangement **1700** is illustrated for the actuation of the slave end effector **1756** in response to movement of the master grip members **1730** of the master control console **150**. It should be understood that the various master and slave positions θ may comprise vectors (in Cartesian space, polar space, joint space, or the like) as well as simple angles or linear separations, and the kinematic chains of the master and slave may be quite different, often even having different degrees of freedom. The amount of following force applied by the operator on the slave are a function of a misalignment between a position (and orientation) of the master input device **1730** and a position (and orientation) of the slave end effector **1756**. The master/slave servomechanism system **1700** relies on a biasing system **1760** that interacts with the operator's hand **1762** to provide tactile feedback to the operator with a feed forward system.

As illustrated schematically in FIG. **17**, the master input device **1730** defines an actual master position $\theta_m{}^a$. The actual master position $\theta_m{}^a$ is transformed by a function f(.) and coupled into the slave portion of the bilateral controller as a desired slave position $\theta_s{}^d$. FIG. **20** illustrates exemplary curves **2001**,**2002** of the function f(.). The amount of force applied by the end effectors of the slave will vary with the difference between the desired position of the slave $\theta_s{}^d$ and the actual position of the slave $\theta_s{}^a$, with the following force on the end effectors increasing with increasing misalignment between the actual and desired positions, often with a proportional relationship.

It should be understood that the schematic representation provided in FIG. **17** of the servomechanism used to effect positional and orientational movement of the surgical end effector may appear quite different in its structural embodiment. For example, a single controller may be used to process both the master and slave signals. The controller can calculate error signals based on the difference between the actual and desired positions in space, and will generate servomotor torque controlling signals based on those error signals. As the master input controller and surgical end effector are moveable in a plurality of orientational and positional degrees of freedom, the calculation of these motor torques may involve vector coordinate transformations such as those described in more detail in U.S. Pat. No. 6,424,885, filed Aug. 13, 1999, the full disclosure of which was previously incorporated by reference.

In general, the actual configuration of the master and slave will be measured using potentiometers, encoders, or other position, velocity, and/or acceleration sensors affixed to rotational joints of the input control devices and slave manipulator. Position information may also be provided by encoders and/or potentiometers affixed to the set-up joints, which may include both rotational joints and linear sliding joints (particularly for the vertical axis). A variety of alternative configuration input mechanisms might be used, including stepper motors, optical configuration recognition systems (for example, using light emitting diodes mounted to the surgical tools and a CCD/frame grabber optical processing system coupled to the endoscope), and the like. It should also be understood that this direct master/slave arrangement will often provide uniform following forces throughout the range of motion of the master and/or slave, regardless of whether the following forces are applied using a system having a single degree of freedom, or a complex input control device and slave mechanism having six degrees of freedom for both the master and slave (optionally even including redundant degrees of freedom for the master and/or slave to avoid singularities).

Referring now to FIGS. **17**, **18**A-**18**B, and **20**, the actual master position $\theta_m{}^a$ is transformed by a function f(.) to derive the desired slave position $\theta_s{}^d$ as discussed previously. Function f(.) takes the form $\theta_s{}^d = f(\theta_m{}^a)$, and is preferably an invertible (monotonic) and continuous function of the actual master position. The function f(.) may artificially increase (or in some cases, may decrease) the calculated error signal once the master grip separation drops below a predetermined point O (where the end effectors touch) to increase the grip strength (or decrease grip strength). This effectively increases (or decreases) the motor torque signals sent from the controller to the motors of the slave. Examples of when it may be desirable to decrease grip strength include the use of low strength delicate tools in which a very small misalignment can produce the maximum following force, so that there would be little tactile indication of grip without decreasing the slope of f.

In the embodiments of the present invention, it is desirable to increase the grip strength below the predetermined point O (the bumper point) to drive the maximum torque to the end effectors. When the tool **400** is mounted or increased grip

strength is otherwise selected by a switch, the function f(.) is shifted from curve **2001** to curve **2002**, for example, so that a greater movement in the slave end effectors can be requested through a larger desired slave position θ_s^d and the maximum torque can be applied to the slave end effectors.

Referring now again to FIGS. **17** and **20**, once the separation between the gripping members drops below a predetermined bump point (arbitrarily indicated at the origin O in FIG. **20**), a small reduction in gripping member separation θ_m^a results in a significantly larger change in the desired position of the slave θ_s^d. The gripping member separation θ_m^a is reduced by squeezing the master grips **350**A-**350**B together. Above the predetermined bumper point O, the actual master position and desired slave position can remain the same, thereby providing the greatest dexterity for the system operator's control over the end effector.

Referring now to FIGS. **20** and **21**A-**21**B, the predetermined force enhancement initiation point O is determined by the configuration of handle **325** and the biasing system **1760**. Similarly, the fully closed or "slammed" configuration of the handle at point P on the curve may be determined by a stop of the handle **325**. The lateral position (corresponding to θ_m^a) of point O will preferably remain unchanged for a variety of different end effectors when different tools are attached to a surgical robotic system. However, as noted above, the actual strengths and intended maximum forces of these different tools may be significantly different.

To allow the control system to drive to maximum joint torque, the processor may revise the function f(.) of the servomechanism. The function f(.) may be selectively revised from curve **2001** where the maximum force position is point P to curve **2002** where the maximum force position is at point P'. This allows the servomechanism to adapt to the tool **400** and achieve maximum torque (essentially unlimited by position) while other tools are driven to a position and potentially never reach the maximum torque limits. When tools are changed, the servomechanism can adapt its control system without having to revise the mechanical configuration of the master controller.

The tool **400** can make use of a memory device or other circuit with memory (referred to herein as "tool memory") mounted in the tool to instruct the master controller to adapt its servomechanism to drive to maximum torque or alternatively a switch may be used to do so. The tool memory can also provide a signal verifying that the tool is compatible with that particular robotic system. The tool memory may also identify the tool-type (whether it is a scalpel, needle grasper, jaws, scissors, clip applier, electrocartery blade, electro-surgical grippers or the like) to the robotic system so that the robotic system can reconfigure its programming to take full advantage of the tools specialized capabilities.

It will be recognized that a wide variety of functions f(.) may be applied to enhance grip strength at the end effectors **812**A-**812**B. In the exemplary embodiment illustrated by curves **2001**,**2002**, function f(.) comprises a linear function directly connecting the maximum force/slam point P or P' with the predetermined force enhancement position O. This allows directly proportional control over the following forces of the slave, and can be substantially reproduced by a biasing system **1760** to provide accurate tactile feedback. Alternatively, more complicated functions might be used. Preferably, the function will be continuous so as to avoid "jumps" in gripping force at the end effectors. Function f(.) will preferably be monotonic and invertible, particularly where force feedback is to be effected using a reciprocal master/slave system, as described above.

To accurately model the forces applied by the end effectors, it should be recognized that the slave position will often be measured remotely (at the motor/sensor location), rather than at the end effector joint. Hence, the compliance of the system will reflect the compliance of a portion of the transmission system. This can be accommodated using the formula $F_s=\theta_s^d(K_{servo}*K_{mech})/(K_{servo}+K_{mech})$ where F_s is the end effector gripping force, K_{servo} is the effective spring constant of the motor, and K_{mech} is the spring constant of the mechanical transmission elements. This equation of F_s may allow robotic system to mimic the stiffness of a particular allow the tool when master grip separation is at a minimum. Surgical tools often flex when fully squeezed. By properly compensating for the spring constant of the motor and mechanical transmission elements, the overall servomechanism can transition from a relationship determined from servomechanism design considerations (when wide open) to a surgical tool-like relationship (when clamped closed).

Referring now to FIGS. **18**A-**18**B, simplified functional block diagrams of servomechanisms **1800**A-**1800**B for driving the end effectors to maximum torque with one servomotor or two servomotors is illustrated. The signal processing used to provide the enhanced grip following forces at the end effectors described above is also illustrated in greater detail in FIGS. **18**A-**18**B.

The servomechanisms **1800**A-**1800**B each include a position derivative (PD) controller **1801**, a torque saturation limiter **1812**, and a torque differential coupler **1814**,**1814'** coupled together as shown. The torque differential coupler **1814** includes a coupling matrix that may vary with the type of robotic surgical tool **400** that is attached to the robotic surgical arm **153**. To drive a pair of end effectors with a single motor **1870**, the servomechanism **1800**A further includes a torque to current converter **1816** and a current limiter **1818** coupled together as shown. To drive a pair of end effectors with a pair of motors **1870**A-**1870**B, the servomechanism **1800**B further includes a first torque to current converter **1816**A and a first current limiter **1818**A coupled together in series to the motor **1870**A and a second torque to current converter **1816**B and a second current limiter **1818**B coupled together in series to the motor **1870**B.

From the master, the actual master grip separation θ_m^a and the actual master grip velocity v_m^a of the master grip members **350**A-**350**B are coupled into the PD controller **1801**. From the slave, the actual slave separation θ_s^a and the actual slave velocity v_s^a of the end effectors are coupled into the PD controller **1801**.

One or more sensors **1866**, **1868** measure the handle separation θ_m by sensing the distance between the master grip member **350**A and the master grip member **350**B to generate the actual master grip separation θ_m^a. The one or more sensors **1866**, **1868** may also measure the velocity v_m as the master grip members **350**A-**350**B are squeezed closed and released to open to generate a measure of the actual master grip velocity v_m^a. The handle **325** may include a stop **1864** to sense the fully closed or "slammed" configuration of the master grips **350**A-**350**B and determine point P on a curve. The handle **325** may additionally include a biasing structure **1860** to provide tactile feedback to a user. The biasing structure **1860** may include a bushing, one or more springs, etc.

The actual master grip separation θ_m^a is processed using the function f(.) **1804**A to provide the desired slave separation θ_s^d as described above. The actual master grip velocity v_m^a may also be modified according to the function f(.) **1804**B to generate the desired slave velocity v_s^d.

The actual slave separation θ_s^a of the end effectors is measured by one or more sensors **1806**A, such as an encoder or

potentiometer of the motor **1870**. The actual slave velocity v_s^a of the end effectors may also be measured by one or more sensors **1806**B, such as a tachometer sensing the velocity of the shaft of the motor **1870**. For the two motors **1870**A-**1870**B of FIG. **18**B, a plurality of sensors **1806**A,**1806**B are used at each motor and combined to determine the actual slave separation θ_s^a of the end effectors and the actual slave velocity v_s^a of the end effectors opening and closing.

The actual slave separation θ_s^a of the end effectors is subtracted from the desired slave separation θ_s^d by the subtractor or negative summer **1808**A to provide a position error signal e^s. The actual slave velocity v_s^a of the end effectors is subtracted from the desired slave velocity v_s^d by the subtractor or negative summer **1808**B to provide a velocity error signal $e^{s'}$.

The position error signal e^s and velocity error signal $e^{s'}$ are respectively amplified by associated gain factors, $K_{p'}$ and K_v by the amplifiers **1802**A-**1802**B. The amplified position error signal $K_{p'}e^s$ and the amplified velocity error signal $K_v e^{s'}$ are added together by the summer **1810** to generate an unbounded joint torque signal τ_J "tau sub j").

The unbounded joint torque τ_J generated by the PD controller can be expressed by the equation $\tau_J = K_{p'}e^s + K_v e^{s'}$. To increase or decrease grip strength and the joint torque, the gain factors $K_{p'}$ and K_v of the amplifier can be varied. To drive the end effectors to maximum torque, the gain factor K_p (such as for curve **2001** in FIG. **20**) was replaced with the increased gain factor $K_{p'}$ (such as for curve **2002** in FIG. **20**) in one embodiment of the invention.

With the increase in the gain provided by the gain factor $K_{p'}$, the unbounded joint torque needs to be limited to the maximum joint torque values. The unbounded joint torque τ_J is coupled into the torque saturation limiter **1812** to generate a bounded joint torque signal τ_J' bounded by an upper torque limit (UTL) and a lower torque limit (LTL).

Referring now momentarily to FIG. **19**, the function of the torque saturation limiter **1812** is illustrated by a curve. If the unbounded joint torque signal τ_J is below the LTL, it is clipped to the LTL level and output as the bounded joint torque signal τ_J'. If the unbounded joint torque signal τ_J is above the UTL, it is clipped to the UTL level and output as the bounded joint torque signal τ_J'. Between the UTL and the LTL, the joint torque signal τ_J is passed through the torque saturation limiter **1812** as the bounded joint torque signal τ_J'.

Referring now back to FIGS. **18**A-**18**B, the bounded joint torque signal τ_J' is output from the torque saturation limiter **1812** and coupled into the torque differential coupler **1814**, **1814'**.

The torque differential coupler **1814**,**1814'** is a coupling matrix to transform joint torque into motor torque. The torque differential coupler **1814**,**1814'** considers the drive mechanics (e.g., drive pulleys, actuating spools, etc.) of the robotic surgical arm **153** and the robotic surgical tool **400** in transforming the joint torque signal τ_J' into a motor torque signal τ_M so that the desired joint torque appears at the end effectors. Thus, it is expected that the coupling matrix of the torque differential coupler **1814**,**1814'** will vary over the different types of robotic surgical tools being used.

For example, the coupling matrix of the torque differential coupler **1814** for the one motor **1870** illustrated in FIG. **18**A will be different from the coupling matrix of the torque differential coupler **1814'** for the two motors **1870**A-**1870**B illustrated in FIG. **18**B. The coupling matrix of the torque differential coupler **1814'** generates two motor torque signals τ_{M1} and τ_{M2} for the two motors **1870**A-**1870**B illustrated in FIG. **18**B. The coupling matrix of the torque differential coupler **1814** generates a single motor torque signal τ_M for the motor **1870**. The motor torque signal τ_M and the two motor torque signals τ_{M1} and τ_{M2} may exceed the capabilities of the motors **1870**, **1870**A-**1870**B, if not for the current limiters **1818**A-**1818**B.

Referring now to FIG. **18**A, the motor torque signal τ_M from the torque differential coupler **1814** is coupled into the torque to current converter **1816**. The torque to current converter **1816** divides the motor torque signal τ_M by a torque constant K_c to generate a motor current I_m. The motor current I_m is coupled into the current limiter **1818**.

The current limiter **1818** limits the motor current I_m that it receives to a motor current $I_{m'}$ to a level below a maximum current limit (MCL) to avoid overheating and damaging the servomotor **1870** from excess current levels. The motor current $I_{m'}$ is coupled to the motor **1870** to produce a torque in its shaft and drive a rotatable driver and an end effector by means of a cable drive system discussed previously with respect to FIGS. **8-11**.

Referring now to FIG. **18**B, the motor torque signals τ_{M1} and τ_{M2} from the torque differential coupler **1814'** are respectively coupled into the torque to current converters **1816**A-**1816**B.

The torque to current converter **1816**A divides the motor torque signal τ_{M1} by a torque constant K_τ to generate a motor current I_{m1}. The torque to current converter **1816**B divides the motor torque signal τ_{M2} by a torque constant K_τ to generate a motor current I_{m2}. The motor current I_{m1} from the torque to current converter **1816**A is coupled into the current limiter **1818**A. The motor current I_{m2} from the torque to current converter **1816**B is coupled into the current limiter **1818**B.

The current limiters **1818**A-**1818**B respectively limit the motor currents I_{m1} and I_{m2} that they receive to motor currents I_{m1}' and I_{m2}'. below a maximum current limit (MCL) to avoid overheating and damaging the servomotors **1870**A-**1870**B from excess current levels.

The motor current I_{m1}' is coupled to the motor **1870**A to produce a torque in its shaft and drive a rotatable driver pulley **828**A and an end effector **812**A by means of a cable drive system discussed previously with respect to FIGS. **8-11**. The bounded motor current I_{m2}' is coupled to the motor **1870**B to produce a torque in its shaft and drive a rotatable driver **828**B and an end effector **812**B by means of a cable drive system discussed previously with respect to FIGS. **8-11**. In this manner two motors are energized to provide following grip forces for each end effector **812**A,**812**B.

As noted previously, FIGS. **18**A-**18**B are simplified block diagrams of the servomechanism control systems for two differing types of robotic surgical tools. The functional blocks of the control systems may be implemented by software routines executing in the computer system **151** of the master console. The signals in this case may be digital signals or vectors that may eventually be converted into analog signals by a digital to analog converter (DAC) such as at the motors. Exemplary software subroutines to execute the functions of the functional blocks of the control systems are described in detail in and shown by FIGS. 13A-13C of U.S. Pat. No. 6,594,552, entitled "Grip Strength with Tactile Feedback for Robotic Surgery", filed by Nowlin et al on Apr. 6, 2000 which has been previously incorporated by reference.

The control systems **1800**A-**1800**B use velocity and velocity error signals which may help inhibit excessive cycling of the system as the slave attempts to follow the master. Hence, these velocity signals represent a viscosity of the system. However, their use may not be necessary, particularly for effecting grip, in light of the small masses and high friction and grip forces that are involved.

Furthermore, while position and velocity error signals were used to compute an unbounded joint torque to compare

against upper and lower limits, the use of a torque or force sensor at the motors or the end effectors of the slave mechanism may better enable the measurement, and hence control, of the force applied by the slave to tissue. Additionally, the use of force sensor at the grip element of the master manipulator may enable the measurement, and hence command to the slave, of the force being applied by the operator on the handle.

Methods of Operation for Maximum Torque Drive

The robotic surgical tool is operated to ensure that a consistent gripping force is attained throughout life of instrument by driving its end effectors to maximum torque limits instead of positional limits.

The end effectors **812**A-**812**B of the electro surgical instrument **400** may be controlled by the operator O seated at the robotic surgical master control console **150** in a number of ways. Typically a gripping or squeezing motion ("master grip") on the master grips **350**A-**350**B of the touch sensitive handle **325** by an operators hand **62** may be used to close the jaws or end effectors **812**A-**812**B of the robotic surgical instruments **400** around tissue. Upon release of the master grips **350**A-**350**B of the touch sensitive handle **325**, the jaws or end effectors **812**A-**812**B open up and reduce the force applied to tissue.

FIG. **21**A illustrates end effectors **812**A-**812**B just engaging a suture S but not yet applying significant forces against the suture. As the cross-sectional thickness of suture S is quite small, the separation between the end effector elements is effectively zero. As no forces are being imposed by the servomechanism, the grip separation angle of handle **325** is also substantially equal to zero. Note that the grip elements need not exactly define a zero angle. At this nominal position, grip elements **350**A and **350**B are just beginning to engage a biasing mechanism **1860**A of a biasing system **1860**. Biasing mechanism **1860**A is here illustrated as an elastomeric bushing surrounding a grip return spring **1860**B. A variety of biasing structures might be used in place of biasing mechanism **1860**A, including springs, magnets, or the like. The biasing mechanism may define a predetermined biasing transition point.

Referring now FIG. **22**A, the force F_{master} applied to the master increases at a predetermined master separation point O'. This biasing system transition point will preferably occur just as the end effector elements touch, and will thereby indicate to the operator the enhanced grip strength being applied by the servomechanism.

Referring now to FIG. **22**B, the end effector grip force F_{slave} is illustrated for the corresponding grip actuation by the master as illustrated in FIG. **22**A, when gripping an object of negligible thickness. Initially there is little end effector grip force F_{slave} up until the bump point O where the end effector grip force F_{slave} increases in response to the slave demand generated by the master.

Referring now to FIG. **21**B, an operator's hand **2162** can squeeze handle **325** beyond the nominal zero angle by compressing bushing **1860**A between the grip members. Once the operator squeezes the handle sufficiently to engage stops **1864** of the grip members, end effectors **812**A-**812**B will preferably be imposing the maximum joint torque at the end effectors and the maximum following force F_m against suture S. This maximum gripping force configuration is designated by the point P' along function f(.) illustrated by the curves **2002** in FIG. **20**A. Advantageously, the reactive forces provided by bushing **1860**A against operator's hand **2162** provide tactile feedback to the operator of the enhanced following forces below the predetermined position O. As described above, function f(.) preferably comprises the identity function above the predetermined position O. It should be understood that the predetermined position O need not define any actual dimensions or forces.

Referring now to FIG. **23**, a flow chart of robotic surgical system setup for a robotic surgical instrument to drive its end effectors to maximum torque limits is illustrated. The method of system setup begins at the start **2300**.

At block **2302**, the robotic surgical instrument or tool **400** is mounted to a robotic surgical arm **153**. The method then goes to block **2304**.

At block **2304**, a memory in the robotic surgical instrument or tool **400** is read out to determine the tool type and to determine if any control system adjustments are to be made to control the cable drive system. The memory may include the upper torque limit and the lower torque limit settings or the tool type may provide an address to the system for looking up the maximum torque limits. The memory may include information regarding the coupling table that is used to transform torque into current or provide an address to the system to where the information in the coupling table can be found. After reading the memory, the method then goes to block **2306**.

At block **2306**, the control system of the robotic surgical system is adjusted to drive a first end effector to a torque in a range between an upper torque limit and a lower torque limit in the case of a single end effector. In the case of two end effectors, the control system may be adjusted to concurrently drive a first end effector and a second end effector to a torque in the range between the upper torque limit and the lower torque limit. In any case, the torque may be a desired joint torque at the pivot pin of the first end effector and the second end effector. An unbounded desired joint torque at the end effectors is bounded to drive servomotors between maximum torque settings. The equation used to generate the unbounded desired torque value is adjusted to saturate more quickly when the touch sensitive grips of the master console are squeezed more tightly around tissue. After the control system adjustments are completed, the method then goes to block **2308**.

At block **2308**, the robotic surgical instrument or tool **400** is operated by the robotic surgical arm **153**. In the case of a single end effector, the first end effector is driven to the torque in the range limited by the upper torque limit and the lower torque limit. The drive pulley to which the end effector is attached is driven to the torque in the limited range of torque. In the case of two end effectors, the first end effector and the second end effector are concurrently driven to the torque in the limited range. The drive pulleys to which the end effectors are attached are driven to the torque in the limited range of torque.

After the end effectors are driven and the robotic surgical procedure is completed, the method goes to block **2399** and ends.

During surgical procedures, such as when sealing vessels, the maximum gripping force at the jaws of the end effectors (torque at the input disks) should be achievable throughout the life of an instrument to ensure consistent vessel sealing by adjusting the controls system to drive to maximum torque levels regardless of cable stretch. Driving to maximum torque levels assures that tissue is clamped with a high grip force for various surgical procedures. One such procedure may be to seal tissue closed. In this case, a bipolar electrosurgical robotic tool may be used with a bipolar generator. The maximum torque levels may be automatically set by the mounting of the tool to a robotic surgical arm or they may be selectively set by an independent switch such as a push button switch or

a dependent switch such that the higher grip forces are activated with the bipolar generator.

Referring now to the flow chart of FIG. **24**, an exemplary operation of the robotic surgical system with the capability of driving end effectors to maximum torque is now described. The method starts at block **2400** and goes to block **2402**.

At block **2402**, the robotic surgical instrument coupled to the robotic surgical arm is calibrated prior to a robotic surgical procedure. During such calibration or initialization, a pair of end effectors may be driven to determine a bump point. The bump point is the position of the input disks where a first end effector and a second end effector just close together and touch each other with substantially zero force. This is the point where the torque is applied to apply a force at the tips of the end effectors. After calibration, the method goes to block **2404**.

At block **2404**, the grips of the touch sensitive handle are first squeezed to close the first end effector and the second end effector around tissue without applying significant force to the tissue. After closing around the tissue the method goes to block **2406**.

At block **2406**, the grips of the touch sensitive handle are squeezed further to apply additional torque to the first end effector and the second end effector to apply a tip force to the tissue. If a vessel, the vessel may begin to close by the tip force. After starting to apply the tip force, the method goes to block **2408**.

At block **2408**, the maximum torque is applied to the first end effector and the second end effector to generate a maximum tip force to squeeze tightly around the tissue regardless of any cable stretch in the cables of the robotic surgical instrument. After squeezing tightly on the tissue, the method may go to block **2410** if an electro-surgical instrument is being used. If the robotic surgical tool is not an electro-surgical instrument, block **2410** is skipped and the method jumps to block **2412**.

At block **2410**, assuming the robotic surgical tool is an electro-surgical instrument and maximum torque has been applied, electrical energy is supplied to one or both of the first end effector and the second end effector. If supplied to both, a bipolar generator is utilized with the bipolar electro-surgical tool. If supplied to one end effector, a mono-polar generator is utilized with the mono-polar electro-surgical tool. The electrical energy may be supplied to cauterize tissue or to seal tissue closed. The amount of electrical energy supplied may be a function of the impedance of the tissue, the clamping force applied to the tissue by the end effectors, and the time that the electrical energy is to be supplied to the end effectors. After supplying the electrical energy, the method goes to block **2412**.

At block **2412**, a determination is made as to whether or not the grips have been released to reduce the torque at the first end effector and the second end effector. If the grips have not been released but are maintained closed, then the maximum torque is maintained by looping back around to block **2408** where the application of the maximum torque is repeated. If the grips have been released, the method goes to block **2414**.

At block **2414**, the grips have been released and the torque applied to the first end effector and the second end effector is reduced and the method may go to block **2499** and end. Alternatively, the portions of the method after calibration may repeat itself over and over again until the robotic surgery is completed.

While the mounting of the tool is discussed as changing the software settings for torque limited control of the servomotors, the torque limited control of the robotic surgical tool may be selectively enabled by a switch. For example a separate actuator, such as a foot pedal, may be pressed to enable the torque limited control and increase the grip force to apply maximum torque to the end effectors. Alternatively, a button, toggle switch, or momentary switch may be used to toggle between a normal mode of driving the end effectors and a torque limited mode of driving the end effectors.

Locking Mode for Robotic Surgical Tools

Referring now momentarily to FIG. **4**A, during a surgical procedure, the wrist **402** and/or one or more end effectors **414**A-**414**B of the robotic surgical tool **400** may be locked so that movement is constrained. Locking the wrist **402** of the robotic surgical tool may avoid cable overstress and cable breakage when applying a maximum torque to end effectors. Locking or clamping the end effectors **414**A-**414**B allows them to be clamped and ratcheted down around tissue. Once the end effectors are locked or clamped in position, a surgeon may let go of the control input while the robotic surgical system **100** maintains the gripping or clamping force. The robotic surgical system may **100** enter a lock mode so that a surgeon may easily selectively lock and unlock the wrist **402** and end effectors **414**A-**414**B. The robotic surgical system **100** may also exit the lock mode to return the robotic surgical tool **400** to its normal range of motion and degrees of freedom.

In some configurations to achieve a higher torque at the end effectors **414**A-**414**B, less torque is to be applied at the wrist axes to prevent mechanical failure in the grip cables coupled to the end effectors. The lower torque at the wrist axes is achieved by locking the wrist **402** of the robotic surgical tool **400**. Locking the wrist **402** locks the joint orientation degrees of freedom (roll, pitch, and yaw) in the robotic surgical tool. The translation degrees of freedom in the robotic surgical tool **400** is maintained to still allow intuitive control by a surgeon. The end effectors **414**A-**414**B of the robotic surgical tool may also be locked so that a surgeon can perform other tasks with other tools. While the wrist **402** and/or the end effectors **414**A-**414**B of the robotic surgical tool **400** may be locked, the shaft **416** may be free to rotate or linear translate along its axis **450**. Thus, a surgeon may clamp onto tissue with the end effectors **414**A-**414**B in a locked position and then pull or rotate the tissue out of the way, for example. While the locking feature on the grip axis reduces dexterity, it also can reduce surgeon fatigue during certain operations, such as tissue sealing, and ensures continuity of the grip force, such as during a tissue sealing procedure. Moreover locking the wrist **402** of the robotic surgical tool **400** limits the maximum applied torque on the wrist cables (e.g., CL**3** in FIG. **8**) so that a maximum torque may be applied to the end effectors and its grip cables (e.g., CL**1** and CL**2** in FIG. **8**) without failure,

Referring momentarily to FIGS. **2**B, **3**B, and **4**A, in one implementation of the robotic surgical system in the lock or reduced dexterity mode, the outer yaw **215**B, outer pitch **215**A, and insertion axes **215**C,**257** of the robotic surgical arm **158** are still free to follow the control input wrists **352** (see FIG. **3**B) while the roll **450** (see FIG. **4**A), inner pitch A**1**, and inner yaw (A**2**) axes are locked at their mode-entry position. In this manner, a surgeon is still able to move the tip of the robotic surgical tool **400** in the X, Y, and Z directions and control the grip, but is not able to rotate the orientation of the instrument wrist **402**.

The master control console provides feedback to a surgeon when the robotic surgical system is in a lock sensing mode and in a locked mode. When entering the lock sensing mode, an audible beep is generated at the surgeons console and a first icon is placed in the field of view of the stereo display at the

surgeon's console. When entering the locked mode, a second icon is placed in the field of view of the stereo display at the surgeon's console. Alternatively, when entering the lock sensing mode, a flashing icon is displayed and when entering the locked mode the icon becomes solidly displayed, When exiting the respective mode, the respective icons are removed from the display or the icon switches from being solid to flashing. The disabled degrees of freedom (roll **450** (see FIG. **4**A), inner pitch A**1**, and inner yaw (A**2**) axes) are dynamically mapped through a Cartesian transformation back to the control input wrists **352** as a virtual "no-entry" surface, may intuitively provide force feedback to the surgeon at the master about available paths of motion of the robotic surgical tool. That is, the master only allows certain paths of motion so that the wrist does not move.

Referring now to FIG. **8**, the degrees of freedom (roll **450** (see FIG. **4**A), inner pitch A**1**, and inner yaw (A**2**) axes) are disabled to avoid failure of the coupled transmission (e.g., CL**1**,CL**2**,CL**3**) between the respective driven elements **818**A-**818**C and the instrument wrist axes A**1**,A**2**. The cables CL**1**, CL**2** that transmit grip torque are the same cables that transmit yaw torque from the robotic surgical arm motors **802**A-**802**B to yaw the tip of the robotic surgical tool. With the wrist locked in the lock mode, the commanded yaw position of the tip of the robotic surgical tool is not allowed to move in order to prevent cable failure due to excessive force. Thus, the yaw grip cables CL**1**,CL**2** transmit grip torque to the end effectors **812**A-**812**B in lock mode. The torque budget allotted to the yaw axis is substantially reduced to zero to allow for more grip torque for high-grip torque clinical applications, such as vessel sealing. The inner roll and pitch motion of the tip of the robotic surgical tool are not allowed to move as well in the lock mode (a.k.a., reduced dexterity mode) to maintain intuitiveness of the control, even though roll and pitch joint torques are not coupled to the grip cables CL**1**,CL**2** and would not facilitate their failure.

The double-click user interface **2701** is a seamless user interface for switching between the locked mode (a.k.a., reduced dexterity mode) and the normal unlocked mode (a.k.a., full dexterity mode). With dual dexterity modes for the same instrument, the need for an instrument exchange is unnecessary since the same instrument can then be used both for sealing (reduced dexterity mode and high grip strength/max torque) and dissection/manipulation (full dexterity and nominal grip strength).

In order to switch modes, the surgeon quickly closes the grips **350**A-**350**B twice (double click signature) from the open position within a double click time. The double click time is measured by software against and compared to a lock mode threshold time. If the double click time is less than or equal to the lock mode threshold time, an intentional mode change between a locked mode and normal unlocked mode is deemed to occur. Otherwise if the double click time is greater than the lock mode threshold time, the double click is discarded as a false-positive mode change request. In one implementation, the lock mode threshold time is one half (0.5) second.

While in a locked mode (reduced dexterity mode), another aspect of the double-click user interface **2701** involves ratcheting, latching, or locking the grip of one or more end effectors closed and increasing the torque applied to the end effectors. A surgeon can manipulate the end effectors around a vessel to be sealed and apply a large grip command to lock the grip of one or more end effectors clamped around the vessel. The surgeon can then relax his hand while the instrument grip remains continuously closed around the vessel until sealing is completed. Electrical energy may be applied to the end effectors to seal the vessel.

After the grip is locked, if the surgeon moves the master grip again to generate a grip command exceeding the lock grip threshold, the end effectors are unlatched or unlocked. The double-click user interface may be disabled while the grip axis is latched or locked. The disabling of the double-click user interface may avoid accidentally opening the end-effectors around the grip axis or rotating the instrument wrist during vessel sealing.

Referring now to FIG. **27**, a user interface system **2700** including a double-click user interface **2701** may be provided in a robotic surgical system to allow a surgeon to quickly enter and exit locking modes without an additional button or foot pedal to press. The double click user interface **2701** allows a surgeon to quickly switch between a reduced dexterity mode (also referred to as a sealing or lock sensing mode), and a full dexterity mode (also referred to as a dissection/manipulation or normal mode) with a simple double-click of the master grips **350**A-**350**B of the touch sensitive handle **325**.

The double click user interface **2701** may be implemented in software for execution by a computer (e.g., computer **151** in FIG. **3**A). The double click user interface **2701** includes a double click sensing process **2710**, a hard stop sensing process **2711**, and a lock mode state machine **2712** operationally in communication together as illustrated. Optionally, a robotic surgical system may include a mode selection switch **2702** in addition to or instead of the double click sensing process **2710**. The mode selection switch **2702** may be provided by a button or foot peddle at the master control station. The actual master position $\theta_m{}^a$ of the master grips **350**A-**350**B is received by the double click user interface **2700** and analyzed by the double click sensing process **2710** and the hard stop sensing process **2711**.

The double click sensing process **2710** analyzes the actual master position $\theta_m{}^a$ to detect two closure or grip cycles (a double-click) of opening and closing of the master grips **350**A-**350**B by a surgeon within a predetermined period of time T. The predetermined period of time T may be selected to be a short time period to distinguish from normal opening and closing of the master grips. For example, assume grips **350**A-**350**B are open having an initial open angle θ_{m1o}. Within the predetermined period of time, grips **350**A-**350**B are closed to a first closed angle θ_{m1c}. opened to a first open angle θ_{m2o}, closed to a second closed angle θ_{m2c} and opened again to a second open angle θ_{m3o}. Graphically, within the predetermined period of time T, the actual master position $\theta_m{}^a$ may travel twice along the exemplary curves **2001**,**2002** in the upper-right quadrant of the function f(.) illustrated in FIG. **20**. If a double-click is sensed, the robotic surgical system changes from a normal mode to a lock sensing mode.

The hard stop sensing process **2711** analyzes the master position $\theta_m{}^a$ to detect if the movement or closure of the master grips **350**A-**350**B by a surgeon meets or exceeds a predetermined percentage of a hard stop. Hard stops may occur after the biasing mechanism **1860**A is engaged and the bump point O has been reached. Graphically, the actual master position $\theta_m{}^a$ may travel along the exemplary curves **2001**,**2002** in the lower-left quadrant of the function f(.) between point O and point P illustrated in FIG. **20**.

The first hard stop may be a first percentage (e.g., ninety percent) of the angle $\theta_m{}^a$ at the fully closed or "slammed" configuration of the handle at point P illustrated in FIG. **20**. If in the lock sensing mode and the first hard stop is sensed, the wrist **402** is locked and the end effectors **414**A-**414**B are locked. The hard stop sensing process **2711** continues to

analyze the master position θ_m^a of the grips for a second hard stop. Once in a lock mode, the end effectors **414**A-**414**B may be ratcheted further together from the first hard stop up until the second hard stop in one implementation. The second hard stop may be a second percentage (e.g., ninety-five percent) of the angle θ_m^a at the fully closed or "slammed" configuration of the handle at point P. The second percentage and the first percentage may differ or be the same. If the first hard stop and the second hard stop are sensed in the same close action of the master grips, the first hard stop is controlling to lock the wrist and the end effectors. If the second hard stop is sensed in a different close action of the master grips when the wrist and end effectors are locked, the wrist and the end effectors are unlocked and the robotic surgical system returns to a lock sensing mode.

The optional mode selection switch **2702**, when activated, alternatively signals the lock mode state machine **2712** to enter the lock mode to reduce the number of degrees of freedom in the robotic surgical instrument.

As illustrated in FIG. **27**, the modes/states of the lock mode state machine **2712** are coupled to the controller(s) of the slave end effectors and the wrist to respectively control the locking and unlocking of the end effectors and the wrist of the robotic surgical tool.

Referring now to FIG. **25**A, modes/states of the lock mode state machine **2712** are illustrated for one configuration. In a normal mode/state **2501**, the wrist and the end effectors are unlocked and operated normally with the robotic surgical tool having all available degrees of freedom. If a double click **2511**A is sensed by the double clicking sensing process **2710**, the lock mode state machine **2712** changes from a normal mode/state **2501** to a lock sensing mode/state **2502**. If no double click is sensed, the lock mode state machine **2712** remains in the normal mode/state **2501** and continues the double click sensing process as illustrated by return arrow **2510**.

In the lock sensing mode/state **2502** if a hard stop **2514**A is sensed by the hard stop sensing process **2711**, the lock mode state machine **2712** switches or changes from a lock sensing mode/state **2502** to a lock mode/state **2503**. If no hard stop is sensed, the lock mode state machine **2712** remains in the lock sensing mode/state **2502** and continues the hard stop sensing process as illustrated by return arrow **2512**. In the lock mode/state **2503**, both the wrist **402** and the end effectors **414**A-**414**B may be locked in one implementation. That is, in the lock mode/state the lock mode state machine **2712** switchably reduces the number of degrees of freedom in the robotic surgical tool in response to the detection of a double click in the master grips and a hard stop in the movement of the control input mechanism. In the lock mode/state, the lock mode state machine further switchably holds a gripping force of one or more end effectors of the robotic surgical tool in response to the detection of a hard stop in the movement of the master grips. If another hard stop is detected in the movement of the master grips, the lock mode state machine releases a constant gripping force of one or more end effectors.

If in the lock mode/state **2503** the second hard stop **2514**B is sensed by the hard stop sensing process **2711**, the lock mode state machine switches or changes back to the lock sensing mode/state **2502** and the wrist **402** and the end effectors **414**A-**414**B are both unlocked in one implementation. If no second hard stop **2514**B is sensed, the lock mode state machine **2712** remains in the lock mode/state **2503** and continues the hard stop sensing process as illustrated by return arrow **2513**.

If in the lock sensing mode/state **2502** a double click **2511**B is sensed by the double clicking sensing process **2710**, the lock mode state machine **2712** changes back from the lock sensing mode/state **2502** to the normal mode/state **2501**. In the normal mode/state **2501**, the lock mode state machine **2712** continues the double click sensing process as illustrated by return arrow **2510**.

Referring now to FIG. **25**B, modes/states of the lock mode state machine **2712** are illustrated for another configuration. In a normal mode/state **2520**, the wrist is unlocked and operated normally with the robotic surgical tool having all available degrees of freedom. If a double click **2521**A is sensed by the double clicking sensing process **2710**, the lock mode state machine **2712** changes from a normal mode/state **2520** to a locked wrist mode/state **2523**. If no double click is sensed, the lock mode state machine **2712** remains in the normal mode/state **2520** and continues the double click sensing process as illustrated by return arrow **2522**.

If in the locked wrist mode/state **2523** and a double click **2521**B is sensed by the double clicking sensing process **2710**, the lock mode state machine **2712** changes from the locked wrist mode/state **2523** to the normal mode/state **2520**. If in the locked wrist mode/state **2523** and no double click is sensed by the double clicking sensing process **2710**, the lock mode state machine **2712** remains in the locked wrist mode/state **2523** and continues the double click sensing process as illustrated by return arrow **2524**.

If in normal unlocked mode (full dexterity), a double-click signature within the lock mode threshold time causes the robotic system to enter the reduced dexterity mode (lock mode) for the respective robotic surgical tool. Another double-click signature within the lock mode threshold time causes the robotic system to exit the reduced dexterity mode and go back to the full dexterity mode. The surgeon, in this manner, can easily switch back and forth between a sealing procedure and a dissection procedure.

Referring now to FIG. **25**C, modes/states of the lock mode state machine **2712** are illustrated for another configuration. In a normal mode/state **2530**, the grip/end effectors are unlocked and operated normally with the robotic surgical tool having all available degrees of freedom. If a full hard stop **2534**A is sensed by the hard stop sensing process **2711**, the lock mode state machine **2712** changes from a normal mode/state **2530** to a locked grip mode/state **2535**. If no hard stop is sensed, the lock mode state machine **2712** remains in the normal mode/state **2530** and continues the hard stop sensing process as illustrated by return arrow **2531**.

If in the locked grip mode/state **2535** and a hard stop **2534**B is sensed by the hard stop sensing process **2711**, the lock mode state machine **2712** changes from the locked grip mode/state **2535** to the normal mode/state **2530**. If in the locked grip mode/state **2535** and no hard stop is sensed by the hard stop sensing process **2711**, the lock mode state machine **2712** remains in the locked grip mode/state **2535** and continues the hard stop sensing process as illustrated by return arrow **2536**.

Alternate Tool Mode

While a lock sensing mode and a lock mode have been described herein, the user interface of the robotic surgical system may instead respectively provide an alternate tool sensing mode and an alternate tool mode. The functionality of the alternate tool mode may be programmed in response to the type of tool coupled to the robotic surgical system. The alternate tool sensing mode and the alternate tool mode may be entered in various ways through sensing alternate user inputs. The alternate user inputs to initiate the alternate sensing mode and/or alternate tool mode may not be normally sensed or looked for during normal tool operation. The state machine

2712 may be modified to enter the alternate sensing mode and/or alternate tool mode in response to one or more alternate user inputs.

Referring now to FIG. 25D, another configuration of states of a state machine of a user interface for a robotic surgical system is illustrated. The robotic surgical system includes a sensing mechanism to sense and detect alternate types of user input, such as a foot pedal, a button or a switch at the surgeon's console or grip combinations of the master grips at the surgeon's console such as a double click described herein.

In a normal tool mode/state 2540, the robotic surgical tool operates normally within a surgical site. A sensing mechanism/process senses for a predetermined alternate user input 2544A to change the robotic surgical system to operate in an alternate tool mode/state 2545. If the predetermined alternate user input 2544A is not sensed by the sensing mechanism/process, the mode state machine remains in the normal tool mode/state 2540 and continues the sensing process as illustrated by return arrow 2541.

If in the alternate tool mode/state 2545 a predetermined alternate user input 2544B is sensed by the sensing mechanism/process, the mode state machine changes from the alternate tool mode/state 2545 to the normal tool mode/state 2540. If in the alternate tool mode/state 2545 and no predetermined alternate user input is sensed by the sensing mechanism/process, the mode state machine remains in the alternate tool mode/state 2545 and continues the sensing process as illustrated by return arrow 2546.

Referring now to FIG. 25E, a functional block diagram of yet another configuration of states of a state machine 2550 of a user interface for a robotic surgical system is illustrated. The robotic surgical system includes one or more sensing mechanisms coupled to the state machine to sense and detect alternate types of user input, such as a foot pedal, a button or a switch at the surgeon's console or grip combinations of the master grips at the surgeon's console such as a double click described herein.

In a normal tool mode/state 2540, the robotic surgical tool operates normally within a surgical site. A first sensing mechanism/process senses for a first alternate user input 2554A to cause the robotic surgical system to enter an alternate sensing mode/state 2555. If the first alternate user input 2554A is not sensed by the sensing mechanism/process, the mode state machine remains in the normal tool mode/state 2540 and continues the sensing process as illustrated by return arrow 2541. If the robotic surgical system enters the alternate sensing mode/state 2555, a second sensing mechanism/process senses for a second alternate user input 2558A to cause the robotic surgical system to enter an alternate tool mode/state 2545. The first sensing mechanism/process continues to sense for the first alternate user input 2554B again to cause the robotic surgical system to exit the alternate sensing mode/state 2555 and go back to the normal tool mode 2540.

If in the alternate tool mode/state 2545 and a second alternate user input 2558B is sensed by the second sensing mechanism/process, the mode state machine changes from the alternate tool mode/state 2545 back to the alternate sensing mode/state 2555. If in the alternate tool mode/state 2545 no predetermined alternate user input is sensed by the second sensing mechanism/process, the mode state machine remains in the alternate tool mode/state 2545 and continues the second sensing process as illustrated by return arrow 2546.

If the robotic surgical system returns to the alternate sensing mode/state 2555, the first sensing mechanism/process senses for the first alternate user input 2554B to go back to the normal tool mode 2540 and the second sensing mechanism/process senses for the second alternate user input 2558A to return to the alternate tool mode/state 2545.

In the alternate tool mode/state 2545, a number of alternate operational modes in the robotic surgical system may be activated. In one implementation, a gripping force applied by end effectors of the robotic surgical tool is decreased so that delicate tissue may be manipulated appropriately by the end effectors. In another implementation, a wrist torque applied at the wrist of the robotic surgical tool is decreased so that a softer wrist is provided to appropriately manipulate delicate tissue. In still another implementation, the alternate tool mode/state 2545, locks the wrist but without applying any additional force to the end effectors. In another implementation of the alternate user mode, the grips or end effectors are locked together while maintaining the wrist motion in the robotic surgical tool. In yet another implementation, when in the alternate tool mode/state 2545 an alternate view from another camera or a different view angle of a camera may be selected. In another implementation, the alternate tool mode/state 2545 may bring up an overlay onto the stereo video screens at the surgeon's console so that a surgeon is provided additional on-screen information. In still another implementation, the alternate tool mode/state 2545 may lock other axes of rotation such as to lock the outer pitch 215A, yaw 215B, and insertion 257 along pivotal axes of a robotic surgical arm 158 (see FIG. 2B) with a robotic surgical tool 101A. In another implementation, entry into the alternate tool mode/state 2545 may start a data logger to log certain data received or generated by the robotic surgical tool. Exiting the alternate tool mode/state may end the data logging of the data logger. In still another implementation, entry into the alternate tool mode/state 2545 may start a video capture of frames of video data from one or more cameras to record a video of the surgical site. Exiting the alternate tool mode/state may end the vide capture and the recording of the video. In yet another implementation, the entry into the alternate sensing mode/state 2555 may open a down drop menu from which a user could subsequently select using the second alternate user input to enter the alternate tool mode. This may be used when a robotic surgical instrument has additional capabilities that may not be controlled or selected by the limited number of normally available user inputs. For example, an additional servo motor may be controlled in the alternate tool mode to provide another degree of freedom, a force sensing instrument may be controlled in the alternate tool mode, or a thermal sensing instrument may be controlled in the alternate tool mode.

Double Click User Interface Method

Referring now to FIG. 26A, a method of using the double click user interface is now described.

At block 2601, the jaws (end effectors) of the robotic surgical tool are calibrated.

At block 2603, the lock sensing mode is entered by double clicking the master grips of the touch sensitive handle. The lock sensing mode may also be entered into by a mode selection switch.

At block 2605, the master grips of touch sensitive handle are squeezed to a full hard stop to enter a lock mode for the robotic surgical tool.

At block 2607, the master grips of the touch sensitive handle are squeezed to a full hard stop for a second time to exit the lock mode for robotic surgical tool, thereby re-entering the lock sensing mode.

At block 2609, a determination is made as to whether or not lock sensing mode is to be exited. If so, the method goes to

block **2610**. If not, the method goes to block **2603** and repeats blocks **2603**, **2605**, **2607**, **2609**.

At block **2610**, the lock sensing mode is exited by double clicking the master grips of the touch sensitive handle. Alternatively, the lock sensing mode may be exited through the mode selection switch.

Referring now to FIG. **26**B, a method of operation of the double click user interface is now described.

At block **2631**, the lock mode state machine is initialized.

At block **2633**, sensing of the double clicking of the master grips of the touch sensitive handle or sensing for another mode selection signal by another mechanism is performed to enter lock sensing mode. Then, the process goes to block **2635**.

At block **2635**, a determination is made as to whether the double click or other selection signal has been activated to enter the lock sensing mode. If not, the process returns back to block **2633** to continue sensing for a double clicking of the grips. If the double click or other selection signal has been activated to enter the lock sensing, the process goes to block **2637** and block **2644** which are performed in parallel.

At block **2637**, sensing for a full hard stop of the master grips of the touch sensitive handle is performed to enter the lock mode for the robotic surgical tool. Then the process goes to block **2639**.

At block **2639**, a determination is made as to whether a full hard stop occurred to enter the lock mode for a robotic surgical tool. If not, the process returns to block **2637** to continue sensing for a full or predetermined percentage of a hard stop of the master grips to enter the lock mode. If so, the surgery may be performed with the robotic surgical tool in the lock mode and the process goes to block **2640**.

At block **2640**, sensing for a full or predetermined percentage of a hard stop of the master grips of the touch sensitive handle is again performed to exit the lock mode for the robotic surgical tool. In this case, the surgeon may have completed the task and desires to exit the lock mode to have full dexterity of the robotic surgical tool. The process then goes to block **2642**.

At block **2642**, a determination is made as to whether another full or predetermined percentage of a hard stop occurred to exit the lock mode for the robotic surgical tool. If so, the process goes to block **2644**. If not, the process goes back to block **2640** and continues to sense for the next full or predetermined percentage of a hard stop in the master grips of the touch sensitive handle.

At block **2644**, sensing for another double clicking of the master grips of the touch sensitive handle or other mode selection signal is performed to exit the lock sensing mode. Then, the process goes to block **2646**.

At block **2646**, a determination is made as to whether the double click or other selection signal has occurred to exit the lock sensing mode. If not, the process returns to block **2644** and sensing continues for a double clicking of the master grips. If so, the process returns to block **2633** and senses for a double click of the grips to enter the lock sensing mode.

With a double click user interface, the robotic surgical tool **400** may be used for dual purposes including vessel sealing with reduced (e.g., three) degrees of freedom and dissection with full (e.g., six) degrees of freedom. The double-click user interface allows a surgeon to more efficient quickly switching between vessel sealing and normal operation without taking his head out of the master control console or using a foot pedal switch with other control functions. The double click user interface and the lock modes may reduce development time by leveraging an existing architecture for a robotic surgical system. The double click user interface and the lock modes may reduce surgical procedure time by saving an instrument change. Furthermore, the click user interface and the lock modes may reduce instrument costs for vessel sealing procedures in a robotic surgical system.

CONCLUSION

One or more elements may be implemented in software to execute on a processor of a computer system. When implemented in software, the elements of the embodiments of the invention are essentially the code segments to perform the necessary tasks. The program or code segments can be stored in a processor readable medium or transmitted by a computer data signal embodied in a carrier wave over a transmission medium or communication link. The "processor readable medium" may include any medium that can store or transfer information including an optical medium, semiconductor medium, and magnetic medium. Processor readable medium examples include an electronic circuit; a semiconductor device, a semiconductor memory device, a read only memory (ROM), a flash memory, an erasable programmable read only memory (EPROM); a floppy diskette, a CD-ROM, an optical disk, a hard disk, a fiber optic medium, a radio frequency (RF) link, etc. The computer data signal may include any signal that can propagate over a transmission medium such as electronic network channels, optical fibers, air, electromagnetic, RF links, etc. The code segments may be downloaded via computer networks such as the Internet, Intranet, etc.

While certain exemplary implementations have been described and shown in the accompanying drawings, it is to be understood that such implementations are merely illustrative of and not restrictive to the specific constructions and arrangements shown and described. For example, implementations were particularly described with reference to master grips of a robotic surgical tools but are applicable to other control input mechanisms in the robotic surgical system used to control a robotic surgical tool.

What is claimed is:

1. A method for a robotic surgical system including a master control console and one or more robotic surgical tools, the method comprising:

sensing for a first mode selection signal of the master control console to enter a lock sensing mode;

in the lock sensing mode, sensing for a first hard stop in a first squeezing together of a pair of master grips of a touch sensitive handle, to enter a lock mode for a robotic surgical tool;

in the lock mode, sensing for a second hard stop in a second squeezing together of the pair of master grips of the touch sensitive handle, to exit the lock mode for the robotic surgical tool; and

in the lock sensing mode, sensing for a second mode selection signal of the master control console to exit the lock sensing mode.

2. The method of claim **1**, wherein a control input mechanism controls entry into and exit from the lock sensing mode.

3. The method of claim **2**, wherein

the control input mechanism is a mode selection switch,

the sensing for the first mode selection signal is a sensing for a first activation of the mode selection switch, and

the sensing for the second mode selection signal is a sensing for a second activation of the mode selection switch.

4. The method of claim **1**, further comprising:

locking a wrist of the robotic surgical tool in response to the lock mode.

5. The method of claim 4, further comprising:

ratcheting end effectors of the robotic surgical tool in response to the lock mode.

6. The method of claim 4, further comprising:

clamping end effectors of the robotic surgical tool together and increasing the torque applied to the end effectors in response to the lock mode.

7. The method of claim 4, further comprising:

releasing end effectors of the robotic surgical tool in response to sensing the second hard stop.

8. The method of claim 7, further comprising:

unlocking the wrist of the robotic surgical tool in response to sensing the second hard stop.

9. The method of claim 1, wherein

at least one or more elements of the method are controlled by instructions stored on a computer readable medium and performed by a processor.

10. A method for a robotic surgical system including a master control console and one or more robotic surgical tools, the method comprising:

sensing for a first alternate user input signal from a user controlled input mechanism of the master control console to enter an alternate sensing mode;

in the alternate sensing mode, sensing for a second alternate user input signal from a first squeezing together of a pair of master grips of a touch sensitive handle to enter an alternate tool mode differing from a normal tool mode;

alternatively controlling a robotic surgical tool in response to the alternative tool mode being sensed for the first time; and

in the alternate tool mode, further sensing for the second alternate user input signal from a second squeezing together of the pair of master grips of the touch sensitive handle to exit the alternate tool mode.

11. The method of claim 10, further comprising

in response to exiting the alternative tool mode, sensing for the first alternate user input signal from the user controlled input mechanism to exit the alternate sensing mode.

12. The method of claim 10, wherein

the user controlled input mechanism is a mode selection switch.

13. The method of claim 10, wherein

the user controlled input mechanism is near the pair of master grips of the touch sensitive handle.

14. The method of claim 10, wherein

at least one sensing is controlled by instructions stored on a computer readable medium and performed by a processor.

15. The method of claim 10, wherein the alternate tool mode is a lock mode for a robotic surgical tool and the method further comprises:

locking a wrist of the robotic surgical tool.

16. The method of claim 15, further comprising:

ratcheting end effectors of the robotic surgical tool in response to the lock mode.

17. The method of claim 15, further comprising:

clamping end effectors of the robotic surgical tool together and increasing the torque applied to the end effectors in response to the lock mode.

18. The method of claim 15, wherein the second alternate user input signal was sensed a second time and the method further comprises:

releasing end effectors of the robotic surgical tool.

19. The method of claim 18, further comprising:

unlocking the wrist of the robotic surgical tool in response to sensing the second alternate user input signal for the second time.

20. The method of claim 10, wherein

the alternate controlling is performed by a processor in response to execution of instructions stored in a computer readable medium.

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